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Cockpit Display of Traffic Information and the Measurement of Pilot Workload: An Annotated Bibliography

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16. Abstract

Approximately 80 references relating to pilot workload were selected and summarized as part of the Cockpit Display of Traffic Information (CDTI) studies currently being conducted by the Federal Aviation Administration Technical Center in Atlantic City, New Jersey. A comprehensive search of the scientific literature was conducted using several sources, including books, scientific journals, proceedings of technical meetings, and computerized information retrieval.

Specific topics covered on this annotated bibliography, as they related to CDTI and its concomitant workload considerations, are subjective measures, spare mental capacity, primary task measures, and physiological measures.

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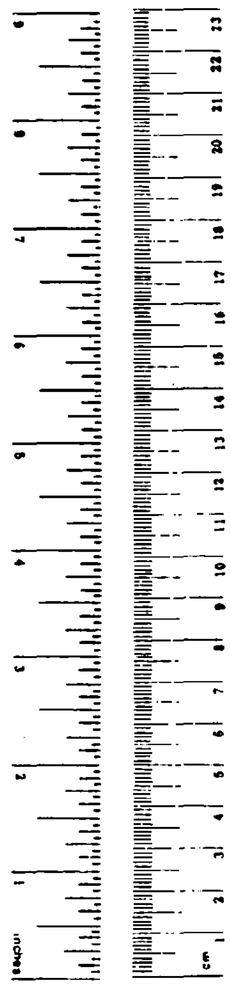
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

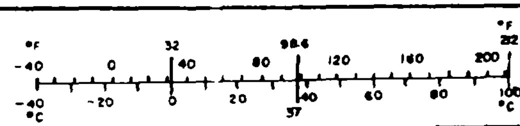
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The author gratefully acknowledges the assistance of Harry Kemp, Librarian at the Federal Aviation Administration Technical Center, for locating relevant sources for this bibliography.

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INTRODUCTION

BACKGROUND.

The Cockpit Display of Traffic Information (CDTI) is a concept which assumes that traffic information can be made available in a pictorial display to the pilot/flight crew. Potential benefits attributable to the CDTI concept have been postulated, including (1) pilot monitoring of air traffic control (ATC), (2) situational awareness with respect to other air traffic, and (3) pilot-assisted spacing and merging. However, operational use of a CDTI device may have certain limitations, such as increased pilot workload, misinterpretation of situations, and distraction from other duties.

PURPOSE.

One of the objectives of the General Aviation cockpit studies of CDTI is to assess pilot workload using objective, subjective, and physiological measures. To this end, this literature search was conducted to enumerate several workload measurement techniques which may have potential application in the evaluation of pilot workload with the operational use of a CDTI.

SCOPE.

Specific topics covered in this bibliography, as they relate to CDTI and its concomitant workload considerations, are physiological measures of workload including heart rate, sinusarrythmia and oculometer analysis; subjective measures of workload highlighting studies in which both structured and unstructured questionnaires and interviews were administered to test pilots evaluating their environment; task analysis; and performance evaluation. The topics of fatigue and noise are touched upon. Only those sources containing information which in some way relates to the project are included. However, it is hoped that the scope of the literature review is broad enough to be of value to other research efforts that are investigating workload.

The sources contained in this bibliography are listed alphabetically by the author's last name. A subject index is also included for the convenience of the user.

Several documents which contain an overview of workload assessment techniques are included. One such article, entitled "Pilot Workload and Fatigue: A Critical Survey of Concepts and Assessment Techniques," by Walter B. Gartner and Miles R. Murphy contains tables which delineate workload and fatigue indicators with references to the literature. These have been abridged and are included in the appendix of this document.

METHODOLOGY.

A comprehensive search of the scientific literature dealing with various topics related to workload assessment techniques was undertaken. Several sources were used for this purpose, including books, scientific journals, proceedings of relevant technical meetings, and technical reports.

Computerized information retrieval and a manual literature search were both conducted to locate the most relevant and current literature. Due to the vast amount of literature available, a self-imposed limitation seemed appropriate; that was, to extract references from approximately 1970 on, except in the case of exceptional sources that could not be overlooked.

COMPUTERIZED INFORMATION RETRIEVAL. The computerized information retrieval system used is available at the Federal Aviation Administration (FAA) Technical Center Library. Several relevant sources were located through the use of the many available data bases. The specific ones accessed were the National Technical Information Service (NTIS), Scisearch, Inspec, Smithsonian Science Information Exchange (SSIE), Physchological Abstracts (PSYCH INFO), and Transportation Research Information Service (TRIS). A brief description of each follows.

NTIS. NTIS data base consists of government-sponsored research, development, and engineering, plus analyses prepared by Federal agencies, their contractors or grantees. It is the means by which unclassified, unlimited reports are made available for sale from agencies like National Aeronautics and Space Administration (NASA), Department of Health, Education, and Welfare (HEW), Housing and Urban Development (HUD), Department of Transportation (DOT), Department of Commerce, and state and local agencies. This data base includes material from both hard and soft sciences.

SCISEARCH. Scisearch is a multidisciplinary index to the literature of science and technology prepared by the Institute for Science Information. Ninety percent of the world's significant scientific and technical literature is included in Scisearch. Citation indexing is provided which allows retrieval of recently published articles through the subject relationships established by an author's reference or prior articles. Scisearch covers every area of the pure and applied sciences.

SSIE. This data base contains reports of both government and privately funded scientific research projects, either currently in progress or initiated and completed during the last 2 years. This source provided information on current research long before initial or followup reports appear in the published literature. SSIE encompasses all fields of basic and applied research in the life, physical, social, and engineering sciences. Ninety percent of the information in the data base is provided by agencies of the Federal Government.

INSPEC. The Science Abstracts (INSPEC) forms the largest English-language data base in the field of physics, electrotechnology, computers, and control. The on-line INSPEC file corresponds to the printed physics abstracts, electrical and electronics abstracts, computer and control aspects, journal papers, conference proceedings, technical reports books, patents, and university theses are abstracted and indexed for inclusion in the INSPEC data bases.

PSYCH INFO. Psychological Abstracts covers the world's literature in psychology and related disciplines in the behavioral sciences. Original research, reviews, discussions, theory, conference reports, panel discussions, case studies, and descriptions of apparatus are included.

TRIS. Transportation research information in air, highway, rail, and maritime transport is included. Subjects included are regulations and legislation; energy, environmental and safety concerns; materials, design, construction and maintenance technology; and operations, traffic control, and communications.

MANUAL LITERATURE SEARCH. A manual search through the literature was also conducted. The journals "Human Factors" and "Ergonomics" proved especially fruitful, as did the text "Mental Workload: Its Theory and Measurement" edited by Neville Moray. This text offers a collection of articles on current research by leading investigators. To supplement the computer and manual search efforts, existing bibliographies on operator workload were consulted. One such source was entitled "A Survey and Analysis of Operator Workload Assessment Techniques" by Walter W. Wierwille and Robert C. Williges. This reference, in addition to contributing a thorough review of the literature, published a listing of relevant Advisory Group for Aerospace Research and Development (AGARD) publications.

SOURCE SELECTION. The criteria for selection of sources included in this annotation were the following:

1. Workload - emphasis on mental workload versus physical workload.

2. Cockpit - (or pilot) as opposed to operator workload per se (i.e., driving a car) unless the information appeared relevant to an understanding of pilot workload in the cockpit.

3. Background - articles providing background information necessary for the development of a mental workload concept or definition.

4. Subjects - only work describing experiments with normal adults, preferably pilots.

5. Application - documents applicable to aircrew mental workload assessment or cockpit workload assessment.

6. Type of Measure - workload measures of interest — physiological, subjective, or behavioral/objective.

In all cases a document, whether it referred to a specific measurement technique, mathematical model, design methodology, or clinical methodology, was included only if specific implications were made regarding mental workload concepts.

RESULTS.

The results of the search efforts are included here in the form of an annotated bibliography. The articles were summarized, and every effort was made to adequately reflect the nature of the information in the text or article, and relevant charts and diagrams were also included. Many authors discuss various workload assessment techniques, detailing their uses, ease of application, and nature of equipment needed. Excerpts from such summary tables have been included, where appropriate. The authors' abstracts are used for three specific references. These include the articles of Jex, McDonnell, and Phatak; McHugh, Brictson, and Naitah; and Spyker, Stackhouse, Khalafalla, McLane. The most striking result of the search is the lack of a clear-cut definition of workload that is generally

valid and practically useful among workload investigators. Therefore, each investigator had to give his own definition, which is mostly very practical, based on the unique situation to be investigated. The annotations contained herein include some situation-specific definitions of workload which the reader may find helpful.

SUMMARY OF WORKLOAD MEASURES

In this section, several workload assessment methods are summarized. Should the reader desire more information on any one method or combination of methods, this can be obtained through a relevant source found in the annotations listed in the Bibliography section of this report. In all cases, techniques summarized refer to the measurement of mental workload as opposed to physical workload.

SUBJECTIVE MEASURES.

The use of subjective opinions are a commonly used measure of workload and include psychometrically defined rating scales, structured questionnaires, open-ended questionnaires, structured and unstructured interviews. Surprisingly, research on the results of subjective measures indicates that these measures are often sensitive and provide meaningful data to the investigator. This is attributed to pilot acceptance which is generally favorable and also to the fact that opinion ratings are not intrusive and can be administered following laboratory or field testing. No special provisions of physical space, portability, data transmission, or integration into the aircraft system are required. In most cases, the subjective rating is used with other measures of workload for greater reliability. Current research in this area is directed toward the development and evaluation of workload-specific rating scales.

SPARE MENTAL CAPACITY.

Another workload measurement technique which falls into the general category of behavioral measures of mental workload (Williges and Wierwille, 1979) is the evaluation of the concept of spare mental capacity. This concept is based on the assumption of a limited channel, sampling model of the human operator (Rolfe, 1974). Spare mental capacity is the difference between the total workload capacity of the operator and the capacity needed to perform the task:

Total workload capacity - capacity needed to perform task = spare mental capacity

This theory assumes that an upper bound exists on the operator's ability to gather and process information. Williges and Wierwille (1979) describe three general methodological approaches for the measurement of workload using the spare mental capacity hypothesis. They are (1) task analytic, (2) secondary task, and (3) occlusion procedures.

Task analytic methods rely heavily on mathematical/theoretical methods from the field of system engineering, and data are usually obtained through laboratory and simulation tests rather than through actual flight evaluation. The underlying assumption is that all task components performed serially require specific lengths of time to complete. If the actual time available for completion exceeds the sum

of theoretical time for performing task components, the inference is that spare mental capacity exists. Stress and task loading occur when time is insufficient to perform the tasks. See Pew (1977), Sheridan and Strassen (1973), and Williges and Wierwille (1979) for a breakdown of specific task analytic approaches and methodology.

The secondary task procedures provide an additional task for the human operator to perform when the main (or primary) task has been attended. Secondary task performance becomes an indirect measure of operator workload based on the theory that performance of the additional task decreases as the attentional demand of the primary task increases. The various secondary task procedures have been classified by researchers into six general areas: (1) nonadaptive, (2) arithmetic logic, (3) nonadaptive tracking, (4) time estimation, (5) adaptive arithmetic logic, and (6) adaptive tracking. See, for example, Jex (1977), Michon (1966), Pew (1977), Jex, McDonnell and Phatak (1966), Jex and Clement (1977), O'Donnell (1975), Ogen, Levine, and Eisner (1979), and Gopher and North (1974).

Some of the criteria for selection of a secondary task include the following points: It should not physically interfere with the task; it should require little training; and it should allow easy scoring.

Occlusion is similar to the secondary task technique in that it is a time-sharing technique and can be used in cases where primary informational inputs are visual. The procedure for using occlusion includes suppressing visual information inputs. For example, the operator may wear a helmet or hat fitted with an opaque visor which can be closed by external control, or the electronic displays can be blanked out to accomplish blocking. Results of driving tests where the occlusion method was used revealed that the less frequent the observations, the slower the speed the driver assumed. The faster the speed, the more numerous were the driver's observations, as would be expected. Studies that used visual interruption to assess driver's sensitivity to degraded conditions found that this method was sensitive to task difficulty and operator skill (see Williges and Wierwille, 1978).

PRIMARY TASK MEASURES.

The major underlying hypothesis for the primary task performance assumes that as the mental workload of a human operator increases the performance of that operator may change, usually in the direction of degradation. Such a change is an indication of increased workload. A secondary hypothesis suggests that successful completion of a mission is a measure of workload in itself. If a mission cannot be completed successfully, then one can infer that the operator is overloaded. Workload studies using primary task measures are divided into three major categories: single measures, multiple measures, and mathematical modeling. For studies utilizing single task measures, see Brictson (1974), Jex and Clement (1977), Senders (1977), Welford (1978), Wierwille and Willigis (1978). For information on multiple task measures, see Rolfe, Chappelow, Evans, Landsay and Browning (1974). The greatest applicability of the primary task measures, whether single or multiple, is in a high workload situation as revealed by various research findings. In a low workload situation, primary task measures have not been demonstrated to be useful due to the fact that the operator adapts to maintain output at an acceptable level. Mathematical modeling studies with workload implications are fairly recent, although mathematical modeling using dynamic or mathematical equations of human operator performance in systems have a longer history (Williges and Wierwille,

Several studies have examined describing functions and similar models in manual control systems. See Jex, McDonnell and Phatak (1966) and Jex (1977) which describe the results of a critical tracking task in conjunction with a describing function model to assess workload.

PHYSIOLOGICAL MEASURES.

In order to measure workload using physiological parameters, equipment used by medical personnel has been used. In addition, certain specific workload measuring devices have been developed. Wierwille (1979) classifies physiological measures and names the following single measures: flicker fusion frequency; galvanic skin response, skin impedance; electrocardiogram, phonocardiogram, plethysmogram; heart rate, heart rate variability, and blood pressure; electromyogram; muscle tension; electroencephalogram; evoked cortical potential; eye and eyelid movements, pupillary dilation; respiration analysis; body fluid analysis; and speech pattern analysis. Multiple physiological measures refers to the combination of two or more techniques. The table below lists the physiological measures addressed in this bibliography and the sources that provide an in-depth description and analysis.

TABLE 1. PHYSIOLOGICAL TECHNIQUES

Technique	Sources
Evoked cortical potential	Spyker, Stackhouse, McLane, Khalafalla (1971) Isreal, Wickens, Chesney (1980)
Eye and eyelid movements	Harris and Christhilf (1980) Young and Sheena (1975) Krebs, Wingert, Cunningham (1977) Ephrath, Role, Stephens, Young (1980)
Pupillary dilation	Kahnemann (1979) Beatty (1980) Krebs, Wingert, Cunningham (1977) Poock (1977)
Multiple measures	McHugh, Brictson, Naitoh (1974) Brictson (1974)
Heart rate, heart rate variability, blood pressure	Boyce (1974) Ettema and Zielhuis (1971) Firth (1973) Hicks and Soliday (1977) Kahnemann (1969) Mulder (1977, 1973) Rohmert, Laurig, Philipp and Luczak (1973) Roscoe (1978)
Galvanic skin response	Kahnemann (1974) Spyker, Stackhouse, Khalafalla (1971)

More complete information on the measures described above can be obtained from the sources mentioned. In addition to specific methodology, many of the sources address limitations of practical application. The professional orientation of the author should be kept in mind, whether it be physiologist, psychologist, operations and research analyst, or systems engineer. The systems engineer may emphasize a particular aspect of workload, for example, the time available to perform a task. Psychologists may emphasize the information processing aspects of mental workload and physiologists may emphasize operator stress and arousal (Williges and Wierwille.) The most inclusive concept of mental workload and its accurate measurement can therefore be obtained through a combination of definitions, concepts, and approaches from all the disciplines that have investigated this topic.

CONCLUSION

It is apparent from a review of the current literature on mental workload that no single definition of workload exists. Rather, each investigator had to give his own definition which is based on the unique situation to be investigated. It is also apparent that to conduct a thorough investigation a combination of measures is recommended which includes objective, subjective, and physiological measures.

BIBLIOGRAPHY

1. Abbott, T.S., Moen, G.C., Person, L.H,, Keyser, G.L., Yenni, K.R., Flight Investigation of Cockpit Displayed Traffic Information Utilizing Coded Symbology in an Advanced Operational Environment. National Aeronautics and Space Administration, Langley Research Center, NASA-TP-1684, 1980.

Traffic symbology was encoded to provide additional information concerning the traffic which was displayed on the pilots' electronic horizontal situation indicators (EHSI). A research airplane representing an advanced operational environment was used to assess the benefit of coded traffic symbology in a realistic workload environment. Traffic scenarios, involving both conflict and conflict-free situations, were employed. Subjective pilot commentary was obtained through the use of a questionnaire and extensive pilot debriefings. These results were grouped conveniently under two categories: display factors and task performance. A major item under the display factor category was the problem of display clutter. The primary contributors to clutter were the use of large map-scale factors, the use of traffic data blocks, and the presentation of more than a few airplanes. In terms of task performance, the cockpit-displayed traffic information was found to provide excellent overall situation awareness.

2. Baty, D.L., and Watkins, A.L., An Advanced Electronic Cockpit Instrumentation System: The Coordinated Cockpit Display. Proceedings of the AGARD Conference on Advancement on Visualization Techniques, AGARD-AG-255, 1980, 11-1-11-11.

A tremendous opportunity for flexibility to the cockpit display designer is available through the cathode-ray tube (CRT) and improved computer technology. This report describes one approach to the replacement of flight instruments which use three separate color CRT's. Each CRT displays information pertinent to one of

the three orthogonal projections of the flight situation. To evaluate this system, three airline pilots made a preliminary assessment. Generally, the pilots accepted the concept of pictorial flight displays. Pilots comments are listed in the paper, along with rankings and ratings.

3. Beatty, J., A Pupillometric Index of Operator Workload. In Biocybernetic Applications for Military Systems, McDonnell Douglas Astronautics Co., St. Louis, MDC-E2191, 1980, 157-174.

One approach to the measurement of workload stems from the observation that momentary workload is directly reflected in the momentary level of central nervous system activation. Pupillometric measures appear to be the most sensitive indicators of activation, and the author discusses the evidence for this contention. The physiological basis is first discussed, followed by perceptual processes, memory, and complex problem-solving, and finally, the implications for workload evaluation in man/machine systems. Results of the experiments described indicate that the more complex and demanding tasks elicit larger task-evoked pupillary responses, thereby enhancing the feasibility of physiological measures of workload.

4. Boyce, P.R., Sinusarrhythmia as a Measure of Mental Load. Ergonomics, 1974, 17, 177-183.

The article describes an experiment that examines sinusarrythmia as a measure of mental load. The experiment involved a subtraction task in which the physical and mental loads could be varied independently. Ten subjects were used in the experiment. All were male graduate research workers in the age range 20 to 40 years. Subjective ratings of task difficulty were obtained (1 = very great difficulty, 7 = very little difficulty), and Wilcoxon matched-pairs t-tests were used to determine the significance.

The author concludes that both heart rate and sinusarrythmia change with both mental and physical load. The changes in heart rate and sinusarrythmia can be regarded as generalized responses to the imposition of a load. The author also states that the conditions in which sinusarrhythmia can be unambiguously related to mental load are few.

5. Brictson, C.A., McHugh, LCDR W., Naitoh, P., Prediction of Pilot Performance: Biochemical and Sleep Mood Correlates Under High Workload Conditions. Proceedings of the AGARD Conference on Simulation and Study of High Workload Conditions, AGARD-CP-146, October 1974, A13-1-A13-8.

The article discusses a preliminary longitudinal study of the factors affecting the carrier landing performance of naval aviators under high workload conditions. Biochemical, emotional, and experimental data were gathered from 26 F-4J pilots. The most significant finding was the effect of high cumulative workload on performance prediction. Under conditions of zero and moderate cumulative workload, more than 70 percent of the variability in individual landing performance could be accounted for by the predictor variable. Under conditions of high cumulative workload, only 40 percent of the individual landing performance could be accounted for by the predictor variables. Also, the pilot's assessment of workload became less predictable under high workload conditions which suggested that either the pilot used a different technique to assess workload under such conditions or marked central nervous activity during high workload interferred with the pilot's assessment.

6. Cameron, C.A., Theory of Fatigue. Ergonomics, 1973, 16, 633-648.

Following a review of the literature on fatigue research, the author concludes that direct attempts to quantify fatigue effects in performance terms are unlikely to prove fruitful. Also, indirect measures, such as physiological indicators of activation level, are likely to be inconclusive, since they are not specific to fatigue. In addition, the severity of fatigue may be most effectively measured by examining the time required to recover from it. It may be necessary to employ physiological measures in order to determine the point in time at which a normal hemeostatic equilibrium is achieved and recovery may have occurred.

7. Caraux, D., and Wanner, J.C., Pilot Workload in the Aircraft of the Future. Journal of Navigation, 1979, 32, 243-258.

This paper, which was presented at a symposium on electronic aids to air navigation held in Paris in November 1977, described the author's detailed analysis of the mental processes of an aircraft pilot, and the human factors that should underlie the design of any flight data display. A cathode-ray tube display is described which was designed for use in civil transport aircraft and the modifications they found desirable following simulator trials.

8. Chiles, W., and Alluisi, E.A., On the Specification of Operator or Occupational Workload With Performance Measurement Methods. Human Factors, 1979, 21(5), 515-528.

Five performance-measurement methods have been described in the literature for use in operator workload specifications: laboratory, analytic, synthetic, simulation and operation-system methods. A review and analysis of these methods indicate that laboratory methods, where appropriate, are usually the methods of choice, with the synthetic work technique especially well suited to examinations of general workload questions. Methodologically, laboratory methods have five highly desirable characteristics: (1) ease and precision of control over relevant performance demands, (2) ease and precision of duplication or replication of conditions, (3) relative ease and precision of measurement, (4) safety and equipment reliability, and (5) relatively low cost with the possibility of selecting tasks of appropriate sensitivity relative to the variables of known operational importance and behavorial potency.

Analytic and synthetic methods appear to yield reasonable results, but both rest on fragile data bases. With correction of this deficiency and further research on time sharing behavior or function interlacing, these methods should prove to be quite helpful. Simulation methods have the potential of providing quite useful information on operator workload, but simulators have not generally been employed for this purpose, and some of the difficulties implicit in their use are discussed. The need for reliable, valid, quantitative criteria to reflect system performance is stressed, and a potentially useful paired-comparisons scaling procedure is described.

9. Chiles, W., Objective Methods for Developing Indices of Pilot Workload. FAA Civil Aeromedical Institute, Oklahoma City, Oklahoma, FAA-AM-77-15, 1977.

This paper discusses the types of objective methodologies that have either been applied, or have potential application to the problem of measurement of pilot

workload, especially as it occurs on relatively short missions. Selected studies that have dealt with the workload measurement problem or some similar problem are reviewed in relation to their applicability to securing answers to operational questions. The types of methods are classified as laboratory, analytic and synthetic, simulator, and in-flight. The paper concludes with a general discussion of relative merits, some of the cautions to be observed in application and in interpretation of the results, with a view toward generalizing to operational situations.

10. Connelly, M.E., Simulation Studies of Airborne Traffic Situation Display Application — Final Report. Electronic Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1977.

This report reviews the results of an extended series of real-time simulation tests at Massachusetts Institute of Technology (MIT), the purpose of which was to evaluate the potential usefulness of displaying traffic and map information in an aircraft cockpit and to ascertain the effects that the availability of such information would have on air traffic control procedures and performance. The program was initiated in mid-1970 and continued for a period of 5 years. A sequence of five distinct research phases was carried out and focused on various individual applications of the Airborne Traffic Situation Display (ATSD). This report presents an overview of the entire effort and a final assessment of the anticipated role of the ATSD in future air traffic control systems. Certain applications of the device, such as guidance on the airport surface and monitoring operations on closely-spaced parallel runways, have not been documented in previous reports, hence these areas are discussed in greater detail.

11. Eggemeier, F.T. Some Current Issues in Workload Assessment. Proceedings of the Human Factors Society - 24th Annual Meeting, 1980. 669-673.

The purpose of this paper is to discuss (1) effects of operator strategy on the levels of load experienced by the operator, and (2) conceptualizations regarding the nature of operator capacities and resources. Various current positions related to these two issues are presented with implications for workload assessment.

The general conclusions reached as a result of the literature search include a view of workload as a multifaceted or multidimensional problem area in which a number of factors combine and interact in order to determine the ultimate workload experienced by the operator. Major elements of workload included within the theoretical framework include system demands, operator strategies, effects of practice on the development of internal anticipatory models of the system, capacities of the operator, and effort expended by the operator in performance of the task. To effectively measure workload and validate results, measures of each of the above elements need to be developed including a variety of performance-based, subjective, and physiological methods for assessment of workload which have potential application to major elements within the framework.

12. Ephrath, A.R., Role, J.R., Stephens, A.T., and Young, L.R., Instrument Scan — Is it an Indicator of the Pilot's Workload? Proceedings of the Human Factors Society - 24th Annual Meeting, 1980. 257-259.

Three NASA test pilots served as subjects in these experiments which investigated the relationship between an aircraft pilot's visual scanning of instruments and his

level of mental activity during a simulated approach and landing. The subjects were presented with a primary piloting task, an arithmetic task designed to control mental loading, and a side task for calibration of the mental loading task. The subjects "look" point was obtained by using a highly modified oculometer system. The pilot's eye scan of the instruments was sampled and recorded at 31-millisecond intervals.

Results of the side task showed a definite increase in workload when the arithmetic task was introduced. The x-y plots of pilot look point for each segment of the approach also show substantial qualitative differences between the different levels of loading.

Preliminary results were obtained with fixation-sequences of length k = 1,2,3 and 4. These suggest a monotonic trend in the value of the entropy as the mental loading increases.

Further work is being done in which eye-scanning data will be calibrated against physiological measures of workload, and in which the difficulty of the primary task will remain constant throughout the entire run rather than through a segment (using tasks like holding patterns and spiral climbs.)

13. Ettema, J.H. and Zielhuis, R.L. Physiological Parameters of Mental Load. Ergonomics, 1971, 14, 137-144.

In the concept of mental load, it is not the complexity of a task but the amount of information handled per unit time (the intensity) which determines the mental load, creating a strong analogy between mental and physical load. Essential aspects of the term "load," as used in work physiology, can be generalized to mental load in the following ways:

1. Questions of the physiological "costs" (i.e., biological consequences) of a given performance.

2. External load to be measured in units of performance/time (signals/minute, choices/time).

3. Physiological changes correlating with the load.

4. Pathological symptoms due to extreme load, such as irritation, disorientation, violent behavior, and psychosomatic illnesses.

In order to study the effect of several conditions of mental load on heart rate; i.e., sinusarrythmia, blood pressure, and breathing rate, an experiment was conducted using a simple binary choice task to induce mental load.

The recording of heart rate, sinusarrythmia and breathing rate was continuous; that of blood pressure discontinuous.

The results indicate that all tasks were performed correctly by all of the subjects when a tolerance of maximal 3 percent mistakes was accepted. For each of the parameters measured, there appears to be a rise in heart rate, systolic and diastolic blood pressure, and breathing rate, and a suppression of the sinusarrythmia score during mental load. The author states that the findings, along with results of other experiments cited, support the hypothesis that mental load induces an increase in the activity of the sympathetic nervous system.

14. Firth, P.A., Psychological Factors Influencing the Relationship Between Cardiac Arrhythmia and Mental Load. Ergonomics, 1973, 16, 5-16.

A survey of recent publications was conducted and results suggest that the proposed relationship between cardiac arrhythmia and mental load is affected by the following:

1. The absence of an agreed definition of mental load makes interpretation of heart rate variability data and its correlation with other measures difficult.

2. Factors such as dynamic and static workload respiratory rate, emotion and age have been shown to influence heart rate variability.

3. There is more than one method of expressing heart rate variability in numerical terms. Each expression is formulated to emphasize different aspects of variability, such as amplitude or frequency, and also to differ as to whether they are weighted for mean heart rate.

In addition, the complexity of the psychological factors which may influence task difficulty is discussed with reference to second-by-second changes in heart rate variability.

The paper concludes with the following points: The need for a better understanding of the task and the related environmental and emotional factors; i.e., task content and demand on the individual, and the need for a greater understanding of heart rate variability as a physiological response.

15. Gartner, W.B. and Murphy, M.R., Pilot Workload and Fatigue: A Critical Survey of Concepts and Assessment Techniques. Moffett Field, California: National Aeronautics and Space Administration, Ames Research Center, NASA TN D-8365, 1976.

The report covers a conceptual analysis of pilot workload and fatigue, an overview of assessment techniques, and a critique of the same. A discussion follows on the management of unwanted workload and fatigue effects in the workload environment. The authors constructed tables in which they delineate indicators of workload and fatigue. These tables and references to literature, using the particular indicator that is cited in the tables, are included in the appendix of this document.

The central difficulty, noted by the authors, was the lack of any widely accepted and applied criteria for establishing functional relationships between indicators and concepts. That is, measures of fatigue and/or workload are selected on the basis of theoretical interest, as opposed to relevancy in a particular conceptualization.

Despite conceptual and practical difficulties, however, attempts to develop and apply useful measures of pilot workload are being vigorously pursued. Several alternative concepts and approaches to the problems are reviewed, with recommendations for followup.

16. Gawron, V.J., The Effects of Noise: A Review. Proceedings of the Human Factors Society - 24th Annual Meeting - 1980, 233-237.

The effect of noise on performance is generally contradictory. Some studies indicate that noise degrades performance, others show no effect, while others demonstrate a facilitation of performance. Relevant research in the field of noise and its effect is presented and reviewed in this paper. Studies reviewed suggest that noise effects are complex and may be influenced by many variables. Subject, task, measurement, and noise characteristics may all interact to produce the notable inconsistency in results. The author summarized her findings of the literature review to say that the final explanation may be a compromise between previously opposing points of view.

17. Gerathewohl, S.J., Brown, E.L., Burke, J.E., Kemball, K.A., Lowe, W.F., and Stackhouse, S.P., In-flight Measurement of Pilot Workload: A Panel Discussion. Aviation, Space, and Environmental Medicine, June 1978, 810-822.

A group of United States scientists engaged in in-flight measurements of pilot workload discussed the problems and aspects of workload (including the techniques used for in-flight measurements) and various workload models (including design-oriented, operational, psychological and physiological concepts). Different experimental approaches were discussed. Experiences, results, and further plans as identified during the 48th Annual Scientific Meeting of the Aerospace Medical Association in Las Vegas, Nevada, May 10, 1977, were also discussed. Contributions by each presenter are summarized.

18. Gerathewohl, Ph.D. J., Definition and Measurement of Perceptual and Mental Workload in Aircrews and Operators of Air Force Weapons Systems: Status Report. Proceedings of the AGARD Conference on Higher Mental Functioning in Operational Environments. AGARD-181, October 1975, C1-1-C1-7.

Dr. Gerathewohl accepts the definition of pilot workload given by Jahns (1972) who defines workload, in his review of the subject, as "...an integrative concept for evaluation of the effects on the human operator associated with the multiple stresses occurring within man-machine environments." Further, he divided the concept into three functionally-related components: (1) input load, (2) operator effort, and (3) work results.

Various methods of measuring pilot and aircrew workload using psychological, physiological, and operational criteria are covered, including a summary of some results obtained from studies utilizing various techniques. In spite of some valuable results, workload measurements associated with highly complex and demanding conditions, including the introduction of new and sophisticated equipment, remains a difficult task.

19. Glines, C.V., A Statesman-Like Challenge. Airline Pilot, 1978, 47, 6-13.

This article is a report on an ALPA-sponsored symposium entitled "Man-Machine Interface: Advances in Workload Study" which was the first initiative within the aviation community to bring psychologists, physiologists, and other biomedical and behavioral specialists to explore the basics of workload and possible applications to the cockpit environment. One of the issues addressed at the conference was a definition of workload and acceptable ways of measuring it.

20. Goerres, H., Subjective Stress Assessment as a Criterion for Measuring the Psychophysical Workload on Pilots. Proceedings of the AGARD Conference on Methods to Assess Workload. AGARD-CP-216, 1977, B11-1-B11-8.

The author first defines the term "psychophysical workload" as comprising the effects of the "total" workload on the human organism, human behavior, and subjective feeling. Psychophysical workload, induced by an activity, will not only depend upon duration and intensity of stressing stimuli, but also upon intra-individual factors in the stressed subject himself (physical features, functioning of the sensory organs, vegetative status and present state of health as a pre-requisite to physical performance; job related knowledge, abilities, skills, need for achievement, experience, and emotional stress resistance as psychic and mental determinants of strain).

Time constraints allowed only the use of subjective assessments of workload situations through standardized interviews and questionnaires administered to 217 pilots; including jet pilots, multiple engine prop pilots, single engine prop pilots, and helicopter pilots.

The author readily points out that subjective opinions cannot be a substitute for objective scientific observations of measurements, but do provide a useful source of information, especially as an adjunct to, in cases where scientific measuring is impossible for any reason.

Findings indicate that the physical workload in its entirety is unanimously assessed lower by pilots than mental and emotional "psychological" workload.

21. Gopher, D., and North, R.A., The Measurement of Attention Capacity Through Concurrent Task Performance with Individual Difficulty Levels and Shifting Priorities. Illinois University, Aviation Research Lab, ARL-74-13, 1974.

Unsolved problems in the application of secondary task techniques include the evaluation of relative changes in performance in dual task situations, the prediction of possible interactions between different tasks and their components, and the extent of voluntary control of capability allocation. This article describes a three-part experiment in which an effort was made to address these problems by a new methodological approach. The three successive phases included (1) separate performance of the experimental tasks with adaptive adjustment of difficulty, (2) simultaneous performance of the tasks with equal task priorities, and (3) simultaneous performance with several manipulations of the two task priorities. The tasks used for the experiment were a single-axis, compensatory tracking task and a digit-processing, reaction time task.

22. Gunning, D., The Measurement of Aircrew Task-Loading During Operational Flights. Proceedings of the Human Factors Society 24th Annual Meeting, 1980, 249-252.

The use of task analytic techniques, as methods for assessing operator workload, is discussed. Task-loading data were collected during four operational flights of the Air Force's KC-135 tanker aircraft, using a Datamyte data recorder which observers used to record the occurrences of 45 different tasks, and performance by the pilot, copilot, and navigator. (The Datamyte is a hand-held unit with keyboard and 32K of solid-state memory, and has several input modes.)

The raw data were summarized by computing the percentage of time spent on each task. Task-loading profiles for each crew member and peak workload situations that occurred are presented. The author concludes that the task-loading measurement techniques produced useful data especially with reference to the causes of high task loading. Likewise, the limitations of the procedure are cited, with the subjective nature of the observer recording the data being the most serious.

23. Harris, R.L., and Christhilf, D.M., What Do Pilots See in Displays? Proceedings of the Human Factors Society - 24th Annual Meeting, 1980, 22-27.

Based on pilots scanning data and discussions with pilots, general aviation flight instruments have been classified into three categories. The classification is related to the type of information presented, the way the information is used, and the pilot's role as a monitor and controller. Suggestions are made for modifying the instruments of one category to improve the information displayed, so the pilot can more quickly extract the information needed.

24. Hart, S.G., and Wempe, T.E., Cockpit Displays of Traffic Information: Airline Pilots Opinions About Content, Symbology, and Format. National Aeronautics and Space Administration, Ames Research Center, NASA-TM-78601, 1979.

A number of candidate computer-generated cockpit displays of traffic information displays and displays options were simulated statically and were shown to 23 airline pilots who were asked to respond to more than 250 questions about them. The pilots indicated that the amount and complexity of navigation information displayed should increase with altitude and map scale. Terrain information should appear automatically if a pilot's own aircraft descends below the minimum safe altitude and should include only those obstructions within 2,000 feet or less. Few pilots felt that weather information should be displayed on a CDTI, but if it was, it should be a pilot request only. A Chevron-shaped symbol, located so that the majority of the map area was ahead, was preferred. The position, altitude, ground speed, ground track, weight class, and flight path history of other aircraft should be presented graphically by coding the shape of the symbol for other aircraft or presented digitally in data tags displayed at pilot request. All pilots thought that color coding was necessary to recognize different categories of information quickly and accurately. The majority of pilots felt that a CDTI would provide useful information even though its presence might increase their workload, particularly during its introductory stages.

25. Hart, S.G., and Loomis, L.L., Evaluation of the Potential Format and Content of a Cockpit Display of Traffic Information. Human Factors 1980, 22 (5) 591-604.

Airline pilots and instrument rated general aviation pilots served as test subjects. The initial approach was to solicit their opinions about display format, information content, and symbology after viewing more than 100 candidate displays.

Results indicate that it is more difficult and apparently requires more time to evaluate the vertical relationship between two targets than the horizontal relationship. Display features that might contribute to a pilot's ability to perceive the traffic situation correctly, such as flight path predictors, were identified. Other display features for which pilots expressed a preference in the

first experiment (such as ground speed and climb/descend, arrows presented in a data tag, and relative altitude encoding of symbols for other aircraft) did not contribute to improved performance, speed, or accuracy.

The authors concluded that additional research is required to determine the best way to inform a pilot about the vertical relationsip between his/her own and another aircraft. Solutions for further study are suggested.

26. Hicks, J.A., and Soliday, S.M., An Evaluation of Sinusarrythmia as a Measure of Mental Load. Proceedings of the Human Factors Society 21st Annual Meeting, October 17-20, 1977, 191-196.

The main purpose of this paper is to provide an evaluation and validation of sinusarrythmia as a measure of mental workload. Sinusarrythmia refers to the irregularity in the length of the interbeat intervals found in the heart rate pattern of a normal individual sitting at rest. Research in the past indicated that this irregularity disappears as a function of the mental load imposed on the individual. A secondary purpose of the paper was to compare the sinusarrythmia approach to estimating mental workload with a secondary task loading technique. A time-interval production task, presented by Michon (1966) served as the secondary task.

Results validated basic findings reported by Kalsbeek (1971) that sinusarrythmia tends to be suppressed as a function of mental workload. An important aspect of this is that once the mental workload task reaches such a level that it causes a complete suppression of sinusarrythmia it reappears, and the individual will begin to make errors unless there is a reduction in the mental load within a few minutes.

27. Isreal, J.B., Wickens, D., and Chesney, G.L., The Event-Related Brain Potential (ERP) as an Index of Display-Monitoring Workload. Human Factors, 1980, 22, 211-224.

The ERP is a transient series of voltage oscillations in the brain that can be recorded on the scalp in response to any discrete stimulus event. The ERP waveform can be analyzed into a series of components which index the sequence of information-processing activities triggered by the eliciting stimulus. The magnitudes and latencies of the components have been shown to vary as a function of the physical and informational properties of the eliciting event, as well as the subject's cognitive response to the stimulus.

This article describes the use of the ERP as an index of the task workload through the discussion of an experiment in which perceptual load, incurred by monitoring a simulated air traffic control display for discrete events, is assessed. The ERP measures were found to systematically reflect differences in task workload and to covary closely with the reaction time measure.

28. Jacquot, B., Electronic Displays Can Reduce Cockpit Overload. ICAO Bulletin, 1979, 12-27.

The article describes tests by the French government of heads-up and heads-down displays, showing both advantages and drawbacks of such advanced cockpit

presentations. Among the advantages of incorporating electronic displays in the cockpit, the author describes a reduction of workload as a major one. Current cockpit configurations involve a proliferation of instruments. This leads to a dispersion of piloting parameters which requires time-consuming visual scanning by the pilot. In addition, data provided by conventional instruments are not always suitable for flying in normal conditions and are even less suitable for solving special problems that may arise. The conventional instruments fail to give the pilot an overall view which enables him to recognize and respond to the situation.

29. Jex, H.R., A Proposed Set of Standarized Subcritical Tasks for Tracking Workload Calibration in Moray, N. (Ed.) Mental Workload: Its Theory and Measurement. New York Plenum Press, 1977, 179-188.

A set of "subcritical" tracking tasks are proposed as one portion of a battery of different types of tasks, each with graded levels of mental workload, against which investigators could calibrate and validate their measures of workload. The recommended task description is provided, along with mechanization (including controlled element, display, and controls), optional inputs, operating procedures, and evaluation criteria.

The author cautions that, despite many years of research on critical task development and application, the paper's recommendations must be considered tentative.

30. Jex, H.R., McDonnell, J.D., and Phatak, A.V., A Critical Tracking Task for Manual Control Research. IEEE Transactions on Human Factors in Electronics, Volume HFE-7, 1966, 138-145.

"A 'critical' tracking task is developed in which a human operator is required to stabilize an increasingly unstable first order controlled element up to the critical point of loss of control. Servo theory and operator-describing function measurements are used to validate the basic assumptions, and an automatically paced critical task is described. The results show that the task does constrain the operator's behavior as intended and the critical instability depends primarily on the operator's effective time delay while tracking. A number of applications for the critical task are reviewed, including secondary workload research, control, and measurement of operator and controlled element gain, and display research."

31. Jex, H.R. and Clement, W.F., Defining and Measuring Perceptual Motor Workload in Manual Control Tasks. In N. Moray (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 125-177.

Despite the lack of theory available to offer relevant answers to the definition and measurement of perceptual motor workload (PML), a significant body of literature exists on pilot workload. The underlying theme in this literature suggests that "the more unexpected items that must be handled per unit time, the higher the 'mental workload,' up to a point where no further workload can be handled." The authors interpret these observations about pilot workload to make the following hypotheses:

1. Operational manual control systems are typically designed and developed to require far less than the operator or binary limiting capabilities; therefore, performance degradation due to environmental stress or workload is seldom observed, except in emergencies.

2. Intrinsic ability (skill, workload) limits can be measured only under high stress conditions; but the operator's capabilities improve with habituation to such conditions.

3. Workload or skill decrements due to exogenous stresses are most apparent when the operator is near his limiting performance.

4. Specialized control tasks or surrogates for control tasks can be designed to emphasize particular skill or workload factors.

This paper offers support for these hypotheses. First, various terms, such as stress, strain, and PML workload are defined and illustrated. Following a discussion of the interacting conflicts, an operator must resolve in a high workload manual control situation, the concept of a "metacontrol system" is reintroduced; a system which governs operation of the human's multiprocessor, time-shared routines. A series of subsections on controlling and measuring PML follows with numerous examples given. Summaries of some are given in tabular form. Some of the author's relevant work (cross-coupled instability task and psychophysiological measures) is discussed in greater deail. Suggested needs for further research concludes the study.

32. .Johannsen, G., Workload and Workload Measurement. In Moray, N. (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 3-11.

In an effort to define workload, the author divides operator workload into three functionally relatable attributes; input load, operator effort, and performance at work result. (See figure 1.)

The measurement of workload is then described. In order to assess the relative value of different workload measures, one has to distinguish between different loading factors and between different types of effort expenditure (scanning effort, perception effort, decision effort, memory recall effort, etc.).

An approach which permits integration of most of these effort measures is given by the time-line analysis which calculates percent workloading for different channels of the human operator. In addition to a time-line type integrative workload analysis, operator activation-level measures should be taken to assess peak load situations. Subjective effort ratings should be used in any case, as it is often the most reliable overall measure.

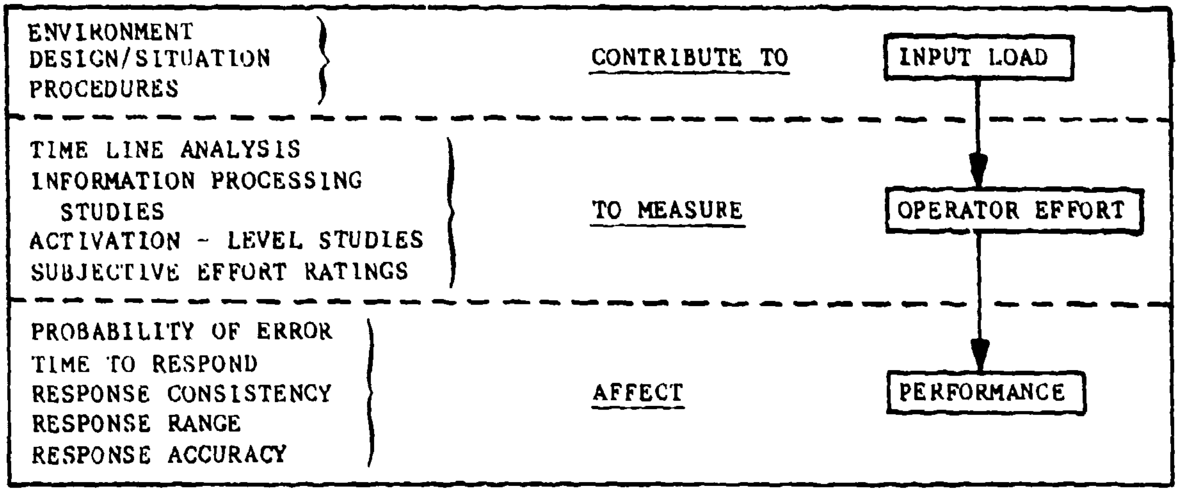

FIGURE 1. ATTRIBUTES OF OPERATOR WORKLOAD AS DELINEATED BY JOHANNSEN

33. Kahnemann, D., Pupillary, Heart Rate, and Skin Resistance Changes During a Mental Task. Journal of Experimental Psychology, 1969, Volume 79, No. 1, 164-167.

This paper describes an experiment in which the subjects performed a paced mental task at three levels of difficulty while recordings of pupil diameter, heart rate, and skin resistance were made. Precise tracking of the changing effort during performance of a mental task was not a unique characteristic of the pupil in this study, although the pupillary response yielded the most consistent results.

The fidelity with which the autonomic variables monitored task demands in this study can most likely be attributed to the use of a paced task and timelocked response measurement. This approach contrasts with the more traditional psychophysiological method of sampling autonomic variables over extended time periods and examining mean differences between experimental conditions in overall levels of activity. It is concluded that there is independent behavioral evidence that the pattern of autonomic activity observed here corresponds to the load imposed by the task.

34. Kalsbeek, J.W., Objective Measurement of Mental Workload: Possible Applications to the Flight Task. Proceedings of the AGARD Conference on Problems of the Cockpit Environment, AGARD-CP-55, 1970, 4-1-4-3.

The problem of objective measurement of mental workload is studied by physiological and pyschological methods. This paper addresses some methods and techniques, together with their application in simulation experiments in order to evaluate cockpit workload. The measures used include heart rhythm, regularity of the heart rate pattern, and distraction stress.

35. Krebs, M., Wingert, J., and Cunningham, T., Exploration of an Oculometer-Based Model of Pilot Workload. National Aeronautics and Space Administration, Contractor's Report NASA-CR-145153, 1977.

Potential relationships between eye behavior and pilot workload are discussed. A Honeywell Mark IIA oculometer was used to obtain the eye data in a fixed-base transport aircraft simulation facility. The data were analyzed to determine those parameters of eye behavior which were related to changes in level of task difficulty of the simulated manual approach and landing on instruments. A number of trends and relationships between eye variables and pilot rating were found. A preliminary equation was written based on the results of a step-wise linear regression. High variability in time spent on various instruments was related to differences in scanning strategy among pilots. A more detailed analysis of individual runs by individual pilots was performed to investigate the source of this variability more closely. Results indicated a high degree of intrapilot variability in instrument scanning. No consistent workload-related trends were found. Pupil diameter which had demonstrated a strong relationship to task difficulty was extensively reexamined.

36. Kreifeldt, J.G., Cockpit Displayed Traffic Information and Distributed Management in Air Traffic Control. Human Factors, 1980, 22(6), 671-691.

The feasibility of graphically displaying traffic information in the cockpit on a CRT is suggested as a viable method for improving the safety and orderliness of the air traffic control system by distributing some of its management to pilots equipped with CDTI. Three experiments conducted at NASA-Ames, using the three-cab simulator facility, are described. The experiments evaluated:

1. Modes of distributed management.
2. Management of mixed CDTI/non-CDTI traffic.
3. Distributed management and curved approaches.

The primary aim was to assess manual, verbal, visual, and total workloads, using both objective and subjective measures. The results showed that pilots on the average preferred the distributed mode of management, contrary to the controllers.

Distributed management based on CDTI produced no detrimental behaviors and exhibited several highly desirable characteristics, such as large reductions in controller verbal workload and smaller interarrival time dispersions than that achieved in centralized management.

The results of the third experiment were the same except that controllers also expressed preference for distributed management, perhaps reflecting the extreme difficulty of the vectoring task in this exercise. Pilots will generally report a large visual workload with CDTI, but still prefer distributed management, indicating that any additional workload caused by CDTI, is more than offset by the additional information and capability it provides.

Controller workload reductions and reduced dispersion times that are common with CDTI-based distributed management indicate increased controller productivity and runway capacity. CDTI also exhibits the potential ability to cope with unplanned contigencies in which the speed and quality of response are essential. The "Who's in charge" syndrome was not observed in the three experiments.

37. McHugh, LCDR W.B., Brictson, C.A., and Naitoh, P., Emotional and Biochemical Effects of High Workload. Proceedings of the AGARD Conference on Simulation and Study of High Workload Operations. AGARD-CP-146, 1974. A12-2-A12-9.

"...A preliminary longitudinal multifactorial study of the interrelationships of biochemical, mood, biographical factors and landing performance under high workload conditions was carried out with U. S. Naval Aviators. Levels of serum cholesterol, serum uric acid, blood lactate, pyruvate, and mood assessments were made during periods of nonflying activity and during periods of increased cumulative workload. Uric acid values fell during moderate cumulative workload, and cholesterol values fell during high cumulative workload. Increased variability of pyruvate and lactate were noted with increased cumulative workload. Increased workload did not affect emotions or performance but altered mood association patterns and altered the relationships of mood and performance. Experience was correlated with performance under zero cumulative workload conditions. Emotion correlated with high performance under high cumulative workload conditions."

38. Michon, J.A., Tapping Regularity as a Measure of Perceptual Motor Load. Ergonomics, 1966, 9, 401-412.

Secondary task may interfere functionally with the main task, without necessarily making use of the same peripheral pathways. The experiments described in this article take the above point into account, and describes test situations in which the subject performs his normal task, and simultaneously taps a pedal as regularly as possible, at a constant rate of about one or two taps per second.

The measure of task performance is the average irregularity, and the basic hypothesis is that tapping performance will become less regular when the main task perceptual motor load increases. Though it is a very simple task to perform, it is very sensitive to disruptions in timing.

39. Moray, N., Models and Measures of Mental Workload. In Moray, N. (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 13-21.

The extent to which a man is loaded is a function not merely of the man, but of the task-specific situation in which he finds himself. There are as many measures as there are types of task, and the hope for a unified theory of load is a false one.

This paper discusses several measures, categorized as normative, empirical and physiological, each capable of evaluating distinct parameters, as well as overlapping ones. The need exists, however, to know the relation between them, the range over which they can be used, ("boundary conditions"), and the population statistics on individual differences.

Problems of methodology and measurement as well as recommendations for future study regarding the formal relation between normative measures, and a corresponding empirical analysis of the interrelation of the scores of the different empirical measures (including the physiological ones) are discussed.

40. Mulder, G., Sinusarrythmia and Mental Workload. In N. Moray, (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 327-343.

Sinusarrythmia is a variability in heart rate, and this variability has been associated with respiration. Recently, more insight into the mechanisms underlying this phenomenon has been obtained, and this paper summarizes these mechanisms. Spectral analysis of sinusarrhythmia has been used, revealing the different mechanisms involved. Different techniques have been used in order to obtain an equidistant time series. This time series is subsequently Fourier transformed either by the indirect method or the direct one.

41. Murrell, J.F., Pilots Assessment of Their Cockpit Environment. Proceedings of the AGARD Conference on Problems of the Cockpit Environment. AGARD-CP-55, 1970, 17-1-17-6.

This study utilized a postal survey method in developing a technique whereby opinions of many pilots could be collated and used. The author notes a low response rate; i.e., 8.5 percent. Therefore, this study of the responses of airline pilots to open-ended questions is regarded as a preliminary investigation. Two hundred and twenty-nine civilian airline pilots responded to four open-ended questions (concerned with design and positioning of instruments, displays, and controls of the aircraft they flew) and one general question. The survey covered nine different aircraft types. Results were subjected to a content analysis and classified according to the item mentioned. Nonparametric tests were used (1) to find the degree of agreement between the pilots as to the relative importance of the different questions and (2) to dispose of the suggestion that the different frequencies of response and, thus, agreement was generated by the fixed question order. Results indicate that the pilot's main concerns are with the design adequacy of his communications and navigation equipment and the instruments presenting flight and engine information and with his own comfort and freedom of movement. The author cautions against generalizations from the results because of the low response rates involved. However, the study does demonstrate that civil airline pilots are particularly concerned about certain areas of their cockpit environment, and they agree about these concerns despite the fact that they fly different types of aircraft.

42. Mulder, G., Mental Load and the Measurement of Heart Rate Variability. Ergonomics, 1973, 16, 69-83.

Results of previous experiments have noted that heart rate variability (HV) diminishes during performance on a binary choice task. These experiments were repeated in the current study in order to find the most sensitive measure that would:

1. Discriminate between the task levels (20, 30, 40, 50, and 60 binary choices per minute).
2. Be stable over days and rest periods (within the experiment).
3. Show the least intersubject variance.

Analysis of variance, carried out over raw scores in the task conditions, showed all measures were significantly influenced by the task conditions. The load in this experiment was the number of binary choices per minute.

Spectral analysis of heart rate variability revealed the existence of a frequency component at about 0.10 hertz (Hz), a respiration frequency, and sometimes a task frequency. In a number of tasks, the respiration frequency increased, and the amplitude of energy in the lower frequencies decreased (decrease in HV).

In future research, more attention should be paid to the type of task, and the behavioral mechanisms involved, and to their presentation mode. Also, it is recommended that in order to arrive at a valid interpretation, measurement of relative thorax volume and blood pressure are indicated. Analysis of single subjects is recommended due to large differences between subjects.

43. O'Conner, S., Palmer, E., Baty, D., and Jago, S., The Effect of Viewing Time, Time to Encounter, and Practice on Perception of Aircraft Separation on a Cockpit Display of Traffic Information. National Aeronautics and Space Administration, Ames Research Center, NASA-TM-81173, 1980.

The concept of a cockpit display of traffic information includes the integration of air traffic, navigation, and other pertinent information in a single electronic display in the cockpit. Two studies were conducted to develop a clear and concise display format for use in later full-mission simulator evaluations of the CDTI concept. Subjects were required to monitor a CDTI for specified periods of time and to make perceptual judgments concerning the future position of a single intruder aircraft in relationship to their own aircraft. Experimental variables included (1) type of predictor information displayed on the two aircraft symbols, (2) time to encounter point, (3) length of time subjects viewed the display, (4) amount of practice, and (5) type of encounter. Results show that (1) length of viewing time had little or no effect on performance, (2) time-to-encounter influenced performance with the straight predictor but did not with the curved predictor, (3) and learning occurred under all conditions.

44. O'Donnell, R.D., Ph. D, Secondary Task Assessment of Cognitive Workload in Alternative Cockpit Configurations. Proceedings of the AGARD Conference on Higher Mental Functioning in Operational Environments, AGARD-181, October 1975. C10-1 - C10-5.

The use of secondary tasks to assess primary task workload is not a new concept, but this paper discusses this concept somewhat differently than the conventional methodology. The goal was to permit valid workload assessment even when the subject was not performing up to "maximal" levels. Rather than requiring failure on each trial, a submaximal workload level was achieved. Use of such known workload levels in the laboratory permits the experimenter to determine the meanings of secondary task changes with respect to manipulations of the primary task load. Once the meanings are established, it is possible to use the secondary task, alone, to evaluate the workload of unknown primary tasks. The item recognition technique, first described by Sternberg (1969), is used.

Results to the study establish the feasibility of using the Sternberg set in the context of a complex primary task which is essentially psychomotor in nature. The author suggests that the next step in probing for sensitivity and validity will require its use with a primary task which is essentially cognitive in nature.

45. Ogden, G.D., Levine, J.M., and Eisner, E.J., Measurement of Workload by Secondary Tasks. Human Factors, 1979, 21, 529-548.

The purpose of the article was to review the post-1965 literature on the use of secondary tasks in the assessment of operator workload. Following a description of the underlying theory, the literature is summarized.

The secondary task technique is used to determine "how much additional work the operator can undertake while still performing the primary task to meet system criteria." The secondary task technique is characterized by an experimental situation in which two discrete and separate tasks are performed concurrently with a clear emphasis on the performance of one of the tasks. Use of the secondary task technique involves comparing the levels of performance obtained when the secondary or loading task is performed alone with the levels obtained on the same task when it is performed with the primary task. The difference between the performances obtained under the two conditions is then taken as a measure or index of the workload imposed by the primary task. The assumption is that the presence of the secondary task does not interfere with the performance of the primary task.

The secondary task technique is also used as a loading task to assess the effects of stress on operator performance. Operators develop strategies of responding in order to contend with task demands. Typical strategies include response selection, response omission, response queuing, criteria modification, and load balancing. Secondary task selection is very important since the type of secondary task employed has a major effect on the response strategies available.

A classification of tasks used in studies measuring workload by secondary task techniques was included in the discussion.

Results of the literature review indicate that research on the use of secondary tasks in the assessment of operator workload has not yet focused upon a single type of secondary task.

46. Palmer, E.A., Jago, S.J., Baty, D.L., and O'Conner, S.L., Perception of Horizontal Aircraft Separation on a Cockpit Display of Traffic Information. Human Factors. 1980, 22 (5), 605-620.

The experimental tasks described in this article required test subjects to judge whether an intruder aircraft would ultimately pass in front of or in back of their own aircraft using CDTI. The results of nine experiments are described. Results of both subjective and objective data reveal that pilot performance in predicting horizontal separation between their own aircraft and an intruder was degraded by:

1. Either aircraft turning when either no predictors were displayed or when the predictors did not include turn-rate information.

2. Increased relative heading of the intruder aircraft.

Performance is improved by:

1. Either ground referenced or own-ship referenced predictors when both aircraft were going straight.

2. Including turn-rate information or both the ground referenced and own-ship referenced predictors when either aircraft was turning.

Finally performance was not affected by:

1. The presence or absence of flight path history, though pilots preferred having history, if the predictors did not include turn-rate information.

2. The presence or absence of ground referenced background, although pilots preferred having some type of background.

3. The rate at which information was updated, although pilots preferred having their own position updated continuously.

4. The speed of the intruder aircraft, although the pilots' response bias did not change.

Certain limitations in research methodology are cited by the authors.

47. Parks, D., Current Workload Methods and Emerging Challenges. In Moray, N. (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 387-422.

Predicting and measuring methods and models for mental workload are among the most urgent needs currently. This paper is concerned with the needs for methods integration, with the intent to convey an appreciation for the display-control-human factors and developmental methods used in design efforts. A basic framework is presented to examine applied problems as a baseline for correlating basic theory and models. The discussion offers an analytic approach used for identifying system requirements and a baseline metric for evaluating workload. The evolution of and rationale for procedures used to identify and organize system requirements, to identify desired crew functions and to select equipment is described.

The use of analytic and workload methods is discussed in context with the system design and development process. The paper outlines a useful approach and identifies representative applied questions, trade-offs, and problems. It also describes some current evaluations of electronic displays and controls to reduce workload. Finally, the concern with methods of integrating and using available techniques to meet the challenge of electronic systems is discussed.

48. Pew, R.W., Secondary Tasks and Workload Measurement. In Moray, N. Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 23-28.

Secondary task methodology derives directly from the limited capacity single-channel hypothesis. To the extent that a second task can be successfully performed concurrently, spare capacity is available over and above that required for performance of the primary task.

The author puts forth the ideal case of a primary/secondary task ratio:

$$\%\ \text{workload} = 1 - \frac{\text{quantity of task B concurrently with Task A}}{\text{quantity of Task B performed alone}}$$

Note: Task A = primary task
Task B = secondary task

The reasons why this ideal has never been achieved in practice are discussed. Methods of developing measurement scales for Task B are also discussed. They are (1) using scales based on quality of Task B performance, (2) using scales based on percentage of time Task B is performed, and (3) using several versions of Task B that vary in demand for a given quality level.

The author concludes that as long as no better theories or models exist to predict workload on the basis of a priori task characteristics or to clearly identify the dimensions of mental activites that contribute to workload, the best alternative is to adopt a measurement strategy that forces the subject to study only conditions for which the single-channel theory can be used.

49. Philipp, U., Reiche, D., and Kirchner, J.H., The Use of Subjective Rating. Ergonomics, 1971, 14, 611-616.

The article describes an evaluation of workload in air traffic control tasks in which results of physiological data and objective work factors are correlated to the operator's subjective assessment of workload. A scoring method and procedure for observer rating was used to record variations in the subjective feeling of workload. Results of subjective ratings have been related to different measures of information processing. In subjective ratings, both the dimensions "stress of time" and "difficulty of the control task" are positively correlated. There was no significant relation at the 95-percent level between the difficulty as subjectively rated, and the computed difficulty. In all cases, results of objective measures correlated closely with subjective measures. Findings indicate that for the subjective rating of stress in a man-machine system, the method of observer rating is suitable.

50. Poock, G.K., Using Pupillometry as an Indicator of an Operator's Overload. Proceedings of the Human Factors Society 21st Annual Meeting, October 17-20, 1977, 197-198.

Two experiments are described whose results indicate that complexity and mental overload aspects of a job may be determined by analysis of pupillary response.

The results of experiment one suggest that by observing a group of people doing the same job, and observing where the average pupil shows a severe constriction to below a normal level, one might be able to identify points in the job scenario where the operators are mentally overloaded.

Experiment two used a group of transport/helicopter/patrol type pilots versus fighter/attack-type pilots. Each subject was randomly presented a series of 10 slides showing various orientations of a vertical gyro indicator (VGI). Results showed no significant difference in the two groups for pupillary size changes. However, latency of dilation was significant at the 0.0001 level for the slides. The inverted VGI slides caused the latency of dilation to increase much more for the transport/helicopter/patrol type pilots than for the fighter/attack-type pilots.

51. Price, D.L., The Effects of Certain Gimbal Orders on Target Acquisition and Workload. Human Factors, 1975, 17 (6), 571-576.

The effects of three gimbal order on target detection, recognition, identification performance and operator workload were evaluated using eighteen experienced pilots. "Gimbal order" refers to the manner in which a sensor is suspended beneath an aircraft. For this study, a 2-axis gimbal was used, which consisted of a pair of rings pivoted on axes at right angles to each other so that one is free to swing within the other. The three gimbal orders evaluated were roll-pitch, yaw-pitch, and pitch-yaw.

Results indicate that gimbal order affected target detection recognition and identification performance. The pitch-yaw order had the greatest range-to-target scores, and it also had the lightest workload.

52. Rasmussen, J., Reflections on the Concept of Operator Workload. In Moray, N. (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 29-40.

The paper discusses concepts of workload and their applications to the human operator in an automated situation.

Man is a highly adaptive and goal-oriented information processor. Models of his performance in well-adapted situations are mainly models of his environment. Models of his performance must also reflect the limiting properties of his internal mechanisms. The author makes these statements in response to the current tendency to extrapolate from analytical, quantitative models developed for manual skills and sensory-motor responses in vehicle control and apply them to the field of supervisory control disregarding the development of models of human data processing within the fields of artificial intelligence, robotics, and linguistic research. A new philosophy of man-machine systems should be the frame of reference which allows research to draw upon the results from all these different approaches and place emphasis on different human ability.

53. Rault, A., Measurement of Pilot Workload. In Moray, N. (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 417-422.

The experimental set described initially uses a flight simulator with landing tasks and various levels of disturbance and ends with experiments on helicopters. Assessment approaches are: psychological measures (tests-Cooper Harper Scale), physiological measurements (cardiac rhythm, pulmonary ventilation, electromyography (emg) of the neck muscles, and electro-oculgraphy (EOG)), and information theory (the transformation type of approach with the hypothesis of the operator being a single channel).

Conclusions are that psychological measures, such as Cooper-Harper scales over a homogeneous population of 10 test pilots gave satisfactory results. Secondly, regarding physiological measures, the EOG gave the most information. The position of the eyes helped to clarify pilot behavior and establish a model. Shortcomings of physiological measurements, however, are the great intersubject variations.

The information theory approach failed to derive valid measurements of the amount of information processed by the pilot because some of the hypotheses for the use of the classical tools were not valid in actual situations; i.e., linearity, stationarity.

54. Rohmert, W., Laurig, W., Philipp, U., and Luczak, H., Heart Rate Variability and Workload Measurement. Ergonomics, 1973, Volume 16, No. 1, 33-44.

Heart rate (HR) as a more or less suitable indicator of strain is one physiological variable which is analyzed. The term, heart rate variability, implies different kinds of variations of HR which become portions of HR variability. These variations depend mainly on variations of stressors and/or variations of strain. This study focuses on 3 parameters used to describe the phenomenon of heart-rate variation.

Those parameters used were (1) amplitude — as a measure of amplitude variations, the difference between two successive heart rate values; (2) frequency — as a parameter to be attained by counting the number of changes from increasing to decreasing values and vice versa, and (3) variability — as a rate using a certain number of heart beats as a base (50).

The range of the variation of the above parameters is discussed using both laboratory and field investigation results. The analyses demonstrated a correlation between heart rate and their variability. The indication seems to be that when heart rate variability is used as a measure of strain in field research, strain might be under-assessed.

55. Rolfe, J.M., Chappelow, J.W., Evans, R.L., Lindsay, S.J.E., and Browning, A.C., Evaluating Measures of Workload Using a Flight Simulator. Proceedings of the AGARD Conference on Simulation and Study of High Workload Operations. AGARD-CP-146, 1974, A4-1-A4-9.

The paper describes an experiment in which a flight instrument trainer was used to evaluate questionnaire, performance, and activity analysis measures of pilot workload. Attempts were made to distinguish between the physical, perceptual, and mental components of workload. For this purpose, three flight plans were devised of approximately equal duration, differing markedly with respect to the three above components. Six professional pilots flew each flight plan and, after landing, completed questionnaires to assess the workload levels and the task content. During the flight, video recordings were made of the pilot's manual and communication activity. Performance during Instrument Landing System (ILS) approaches immediately before and after the experimental flights plans was also measured.

56. Rolfe, J.M., and Lindsay, S.J.E., Flight Deck Environment and Pilot Workload: Biological Measures of Workload. Applied Ergonomics, 4, 1973, 199-206.

The approach in this study on workload makes three assumptions:

1. All tasks impose workload, in normal as well as abnormal working situations.

2. Workload varies in nature, demanding physical and mental effort; any measure which is used to measure workload thoroughly in an aircraft cockpit should be sensitive to all varieties of workload which will occur.

3. Workload varies from individual to individual.

Based on the above assumptions, the study of workload must be oriented to both task and operator. It may seem logical to place performance measures at the head of any list of workload measures. However, the author points out that they usually reveal only how well some functional system criterion is met, but seldom tell the price paid in operator effort in meeting this criterion. In addition to measures of performance, which indicate how well the task is performed, it is necessary to determine how much it costs the operator to achieve his level of performance. In parallel with performance, other forms of measure more sensitive to the assessment of workload should be considered, such as observational analysis of the subject's performance by trained observers, subjective assessments obtained from the crew, additional performance measures using loading tasks and physiological measures. All of these techniques should be reliable and should not impinge on the operator with the effect that the task being assessed is changed by the presence of the assessment measure; methods should be acceptable to the subject; and results obtained should be easy to interpret.

Of the measures assessed, observation, subjective assessment, and physiological response are the most suitable techniques for use in the flight environment. Also, since research, to date, indicates that no one measure can adequately indicate the nature of the demands the task imposes or the effort expended to meet the demands, a combination of measures is the best solution to the problem.

57. Rolfe, J.M., Whither Workload? Applied Ergonomics, March 1973, 8-10.

One approach to the study of aircrew workload is the use of subjective assessments. By means of a questionnaire, aircrew are asked to indicate the extent and source of their workload during phases of flight. A study was conducted, using the above subjective technique, to compare perceived workload between single seat and multi-crew aircraft. Results reveal the extent to which additional crew members relieve the pilot of certain loads during particular phases of a flight. One limitation to the questionnaire method of obtaining information is that "it gives the minimum of information relating to the nature of the load imposed on the subject in terms of its physical and mental components." Physiological measurement remains nothing more than a reliable source of concomitant material, since variations in activity can be brought about by a number of environmental and subjective factors. The true meaning of physiological changes in response can only be assessed in conjunction with a comprehensive knowledge of the task situation.

The author concludes by stating that in terms of both the definition of workload and the derivation of techniques for its measurement, the investigator should consider expanding his views of the problem to accept the breadth of the topic.

58. Roscoe, A.H., Stress and Workload in Pilots. Aviation, Space, and Environmental Medicine, 1978, 630-636.

Many studies have highlighted the increase in physiological activity which occurs in pilots during flight and especially during takeoff and landing. As an example, it has been clearly shown that a pilot's heart rate increases during the landing approach to reach a peak at, or just before, touchdown. Investigators have attributed these findings to the effects of workload and to physiological or emotional stress. It is important to be able to differentiate between emotion-related and workload-related aspects of flight. In this paper, the author assesses both to determine their relative influence on heart rate.

A number of test pilot's heart rate responses were recorded during various flight trials involving different types of aircraft. It is concluded that heart rate responses in experienced pilots are influenced almost entirely by workload-related factors and not by emotional stressors, such as risk and anxiety.

59. Rosenbrock, F., Hardware Problems in Ergonomics Measurements. Ergonomics, 1971, 14, 617-623.

Assessment of the operator's workload is one of the most difficult and challenging problems in the analysis of the man-machine interface. The problem of workload measurement is further complicated by the necessity of avoiding interference in the work situation.

This paper describes the analyses of an actual problem (the analyses of the task and workload of radar controllers). The application of multichannel automatic data acquisition and processing is utilized. For assessing strain, physiological variables are measured: electrocardiogram (EKG), electro-oculogram (EOG), electromyogram (EMG) of a back muscle and respiration. These variables are correlated with factors of stress and strain using a coding system which is described. The evaluation of a multidimensional work process study is synchronized with the physiological data.

60. Rotondo, Brig. Gen. G., Workload and Operational Fatigue in Helicopter Pilots. Proceeding of the AGARD Conference on Methods to Assess Workload, AGARD-CP-216, April 1977, B1-1-B1-11.

The author describes and analyzes, in great detail, the nature and the entity of various stressing factors that constitute the physical and psychic workload of the modern helicopter pilot. Many of his assessments can be applied to the broader category of pilots in general, and, in fact, the author makes this application. He describes various components of fatigue — physical, psychic, and emotive — and identifies several task-specific causes of fatigue for the pilot, including noise, vibration, acceleration and variations of speed, altitude, pressure, and temperature.

He concludes that flying is not just a technical or operative activity; i.e., a job, but "a vital activity and an 'in toto' reaction of the ego to the environment."

61. Rouse, W.B., Approaches to Mental Workload. In N. Moray (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 255-262.

The author defines workload as a fraction of attention and intensity of effort. The product of these components (i.e., fraction of attention times intensity of effort) offers a reasonable composite definition of workload. Models and measures appropriate to these definitions are considered, including information theory models, control theory models, queuing theory models, performance measures, physiological measures, and subjective measures.

In concluding, the author offers a synthesis of possible approaches to the problem of mental workload. An instantaneous measure of workload w(t) might be given by:

$$w(t) = f(t) \times i(t), \quad 0 \leq t \leq T$$

where f(t) is the fraction of attention, and i(t) is the intensity of effort at time t, and (O,T) is the time interval of interest. The fraction of effort f(t) might be predicted using a queuing model while the intensity of effort i(t) might be measured physiologically or perhaps assessed via subjective measures.

The main benefit of this approach is that it is not limited to highly structured tasks, such as instrument scanning and tracking.

62. Sanders, A.F., Some Remarks on Mental Load. In Moray, N. (Ed.) <u>Mental Workload: Its Theory and Measurement</u>. New York: Plenum Press, 1977, 41-77.

This paper presents an analysis of the concept of mental load from the human performance theory viewpoint.

Following a discussion of the theoretical status of the concept of mental load, an outline is given of the main procedures of measurement. The procedures are subdivided into three main groups: measures of behavior, psychophysiology, and subjective judgment.

The next section describes a number of theoretical bases which are all related to the limited capacity idea. Other capacity concepts (in terms of limited capacity processors and effort) are described. Three types of processors, with varying applications, are outlined.

Finally, current experimental trends are discussed, and it is concluded that a multichannel type of processor, composed of a network of internal mechanisms, is validated by the data. Consequently, mental load cannot be conceived of as a single dimension. Pending applied work in workload measure development, a task may be described in terms of a pattern of mental load.

63. Senders, J.W., Axiomatic Models of Workload. In N. Moray (Ed.) <u>Mental Workload: Its Theory and Measurement</u>. New York: Plenum Press, 1977, 263-267.

The author puts forth several mathematical models of workload, including a simple steady-state model of workload which includes 12 points. He summarizes this model by stating that "workload of a well-defined task is the length of a vector in a space defined by N (number of actions) elemental type workload axes. On each axis is plotted the workload corresponding to that elemental type. Each such elemental workload is computed by taking the ratio of elemental type demand to elemental type capacity."

The other models included are simple nonsteady-state models of workload, load component generated by internal switching, load component generated by external switching, switching loads and time cost, and motivation and effort. Each model is clearly delineated on a point-by-point basis in support of a particular hypothesis.

64. Sheridan, T.B., and Simpson, R.W., Toward the Definition and Measurement of the Mental Workload of Transport Pilots. Flight Transportation Lab/Man Machine Lab, Massachusetts Institute of Technology, Cambridge, Mass., DOT-OS-70055, 1979.

This report describes research at the M.I.T. Flight Transportation Laboratory on problems of defining and assessing mental workload. The primary emphasis is on subjective assessment. One result is the generation of a subjective rating method for pilot workload (under instrument conditions) modelled on the Cooper-Harper rating scale.

The authors point to the changing nature of pilot workload, describing the demands of workload as a "transient" phenomena when, for example, a routine autopilot-monitoring situation suddenly becomes a frantic effort to control an unstable aircraft or avoid midair collision. In ascertaining the nature of mental workload (versus physical workload which is readily measurable by physiological indicators) the authors define a set of workload factors, one for each component of their postulated sensory-cognitive-motor system. These workload values are a function of the overall task demand level and pilot skill. Thus, the authors infer that by determining workload factors, one can predict when overall task performance is about to degrade.

A description of the current task environment and task characteristics of a transport pilot follows the theoretical discussion, along with a summary of objective and subjective workload measures.

65. Sheridan, T., and Strassen, H., Definition, Models, and Measures of Human Workload. In N. Moray (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 219-233.

Following a brief review of workload definitions, empirical measurements corresponding to those definitions are discussed. Measurement techniques include physiological variables, dual or secondary task methods, information measures, task analyses, attention allocation, and subjective measures.

Some metaphors used to characterize the various component concepts of workload are then covered including stress and strain, capacity, and attention allocation. The underlying rationale in the application of each is discussed.

Finally, the formal models with links to mental load are discussed. Those models are the optimal control model, decision models, information channel models, and activation/uncertainty models. The article is characterized by several excellent illustrations (see figure 2 and table 2).

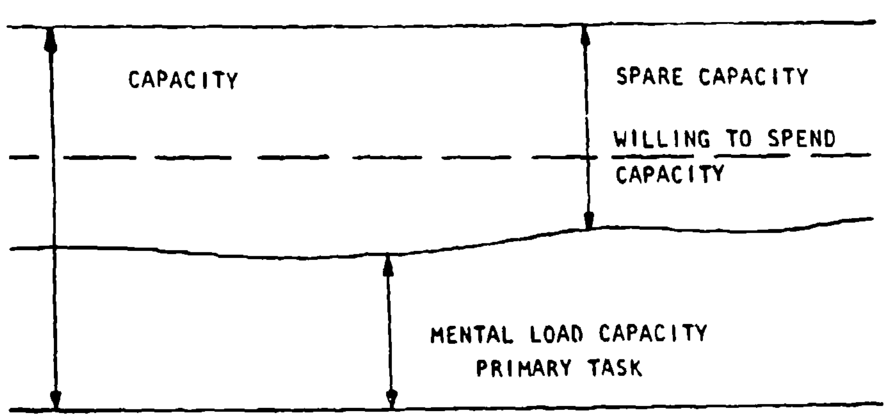

FIGURE 2. THE ONE CHANNEL CAPACITY MODEL

TABLE 2. JUDGMENT OF MENTAL LOAD INDICES ON THE BASICALLY REQUIRED PROPERTIES OF A SENSOR

Methods/Properties	Sensitivity to Disturbances	Influence on Variables to be Measured	Statics and Dynamics Sensor	Accuracy Reproducibility	Remarks in Use
Physiological Variables (M2)	very	none	unknown	poor	easy to use
Dual or Secondary Task Methods (M3)	not likely	maybe, difficult to measure	known	reasonable	easy to use
Information Measures, Task Analyses (M4)	none	none	known	unknown	very difficult
Attention Allocation (M4)	none	very little	unknown	unknown	easy to use
Subjective Measures (M1)	unknown	very little	unknown	reasonable	easy to use

66. Spyker, D.A., Stackhouse, S.P., Khalafalla, A.S., and McLane, R.C., Development of Techniques for Measuring Pilot Workload. National Aeronautics and Space Administration, Contractor's Report NASA-CR-1888, 1971.

"The goal of this study was to provide an objective method of assessing information workload based on physiological measurements. Information workload or reserve capacity, was measured using a visual discrimination secondary task and subjective rating of task difficulty. The primary task was two axis (pitch and roll) tracking, and the independent variables in this study were aircraft pitch dynamics $[(K/S,\ K/S^2,\ \text{and}\ K(S + 1)\ 16\ S/S^2 = 8S = 16)]$ and wind gust disturbances (white noise with cut-offs at 1.5, 2.5, and 4.0 rad/sec.). The study was structured to provide: (1) a sensitive, nonloading measure of reserve capacity, and (2) an unencumbering reliable measure of the psychophysiological state. From these, a measured workload index (MWI) and physiological workload index (PWI) were extracted. An important measure of the success of this study was the degree to which the MWI and PWI agreed across the 243 randomly-presented, 4-minute trials (9 subjects X 9 tasks X 3 replications)."

The somewhat sophisticated physiological observations which were considered were:

1. Electromyogram

2. Respiration

3. Vectorcardiogram (VCG)

4. Skin Impedance

5. Electroencephalogram

6. Eye Movement

A subjective evaluation of task difficulty was used in addition to the above measures. The questionnaire had four multiple choice questions related to the difficulty of the primary task and two questions related to the difficulty of the secondary task. Results of the subjective data show that as the task became more difficult, the subjective evaluation of difficulty also increased.

67. Stave, A.M., The Effects of Cockpit Environment on Long-Term Pilot Performance. Human Factors, 1977, 19 (5) 503-514.

A fixed-based helicopter simulator was used to examine pilot performance under conditions of vibration, noise, and fatigue. Flight periods ranged between 3 and 8 hours, using test subjects with a minimum of 1,000 hours flying time. Results indicated that performance seemed to depend on motivation rather than fatigue; despite the onset of fatigue, performance not only did not degrade, it actually improved with time. The author explains this phenomena in the following way: as pilots feel the onset of fatigue, they put forth increased effort to compensate, which results in an initial improvement in performance.

Subjects in the study suffered from "lapses" resulting in abnormally poor performance. The lapses are short and occur at unpredictable times, perhaps the result of the body's reaction to fatigue products in the nervous system. They are

also attributed to a reduction in the amount of oxygen in the air breathed by subjects which increased the number of blocks and prolonged their duration. A momentary lack of oxygen in the brain will cause a block.

If it can be shown that such "lapses" occur in actual flight, they may provide a probable explanation for many "pilot error" accidents.

68. Steininger, Dr. P., Subjective Ratings of Flying Qualities and Pilot Workload in the Operation on a Short Haul Jet Transport Aircraft. Proceedings of the AGARD Conference on Studies on Pilot Workload, AGARD-CP-217, 1979, B10-1-B10-7.

The article describes the use of two subjective measures used by subject pilots to evaluate cockpit layout and instrumentation. The pilots were employed by a short haul jet transport aircraft company. The measures used included a questionnaire of 82 fixed items answered on a seven-step rating scale and a structured interview covering 19 items. The author addresses the pros and cons of subjective measurement as cited in the literature. Likewise, he points out why objective measures may not always be so valuable as an assessment measure.

He concludes that subjective measures are valuable instruments provided the following criteria are met:

1. The survey should cover an adequately representative sample of pilots.

2. The state of training and experience of the pilots must be taken into consideration as an independent variable that exerts a relevant influence on the way questions are answered.

3. The questions must be carefully formulated and their contents must be unambiguously concerned with an accurately defined element of the system or particular criterion to be judged.

4. The set of questions should be as complete as possible; i.e., must cover not only all the individual elements of the system, but also as far as possible, the dynamic components that occur during the real operation of the aircraft.

5. The set of questions should include a multiple approach in order to cover more than one view of the problems investigated. That means the application of some different kinds of questioning techniques on the same project; i.e., rating techniques, questionnaires, checklists, open comments on prepared questions, and the open interview.

69. Strasser, H., Physiological Measures f Workload Correlations Between Physiological Parameters and Operational Performance. Proceedings of the AGARD Conference on Methods to Assess Workload, AGARD-CPP-216, April 1977, A8-1-A8-7.

Stress defined as input load of man at work may be assessed by means of operational measures and time studies, but strain as the individual output cannot be quantified without considering physiological data. Variability of some physiological parameters, mostly used in the field of workload studies, is described; and its practicality is discussed for application in field studies. Methodological problems and improvements to counteract these problems are also discussed.

In experimental research on stress and strain, very often correlations between operational, physiological, and subjective rating parameters of workload are expected. By means of data from laboratory studies with simultaneously registered physiological and operational performance measures, it is demonstrated when correlations can be found and when they cannot.

The influence of different hypoxic gas mixtures on pursuit tracking and on physiological parameters is studied. From the results, several conclusions can be made. In relatively mild hypoxia, physiological changes are present, but normally are concealed by reactions due to prolonged test time. In spite of statistically significant physiological effects, no noticeable deteriorations of performance in tracking could be measured in hypoxia down to an hypoxic gas mixture of only 13 percent O_2 in inspired air. Not until before 11 percent O_2 significant and mentionable impairments of tracking performance were found.

The same is true of noise. Decreased performance in noise could not be found, but an increased level of heart rate indicated the stress.

Results indicate that physiological indices definitely react, even in low workload situations, in order to bring into action reserves of energy, which will guarantee a normal performance. Only in high workload situations can correlations between performance and physiological measures be expected.

70. Ursin, H. and Ursin, R., Physiological Indicators of Mental Workload. In N Moray (Ed.) Mental Workload: Its Theory and Measurement. New York: Plenum Press, 1977, 349-365.

This paper discusses some available physiological measures and debates whether or not they are applicable to measuring mental load. The main premise of the authors is that it is fairly easy to measure and, therefore, exclude the physical workload and measure psychological activation. However, serious difficulties exist if one tries to discriminate between emotional factors and information workload. If this discrimination is not made, measuring "mental workload" does not involve anything but a conventional evaluation of activation.

More recently, data from animal and human experiments are helpful in furnishing a more refined understanding of the emotional processes. The psychological and physiological processes occurring in threatening and challenging situations show clear dependency on experience and development of coping behavior. In particular, it is important to know at which stage of development of the coping process the individual is, to what extent he evaluates his behavior as coping, how he evaluates his performance, and his motivation to perform in that particular task. The physiological responses recorded are the end results of a very complex psychological matrix. There is some evidence of specificity in the endocrine responses, but these have not been established in any detail.

71. Verstynen, H.A., Potential Roles for the Cockpit Traffic Display in the Evolving ATC System. Society of Automative Engineers Technical Paper Series, 1980.

In this paper, the author begins by providing a few simple definitions ot CDTI concept, starting with the cockpit traffic display itself. He then discusses the multitude of potential uses for CDTI, with special reference to aircraft applications. Some potential passive roles cited for CDTI are increased situational

awareness, blunder detection and recovery, reductions of separations, hardware failure detection, and recovery and automation monitoring. Active roles are pilot-controlled spacing and merging, condition clearances, pilot-controlled primary separation, landing rollout, turnoff, and taxiing of aircraft in low visibility and collision avoidance.

The author concludes by briefly describing the research efforts of both the NASA and the FAA in studying the advantages and disadvantages of CDTI, in a realistic operational environment, for a broad range of aircraft classes and ATC environments.

72. Welford, A.T., Mental Workload as a Function of Demand, Capacity, Strategy, and Skill. Ergonomics, 1978, 21, 151-167.

The author outlines a conceptual framework in order to view the many problems of defining and measuring mental workload. Demand and capacity are the areas on which the paper focuses. Two types of demand are distinguished: the amount of data to be handled at a particular moment, and the amount to be dealt with at a particular time. Capacity and the effects of various factors are considered in relation to concepts of signal-to-noise ratio in the central nervous system. Finally, two approaches to the measurement of workload are compared. In addition, chronic stress and emotions, often overlooked in workload analysis, are briefly discussed as long-term factors liable to affect workload.

73. Wickins, C., Derrick, W., Berringer, D. and Micalizzi, J., The Structure of Processing Resources: Implications for Task Configuration and Workload. Proceedings of the Human Factors Society - 24th Annual Meeting, 1980, 253-256.

With respect to workload assessment, the multidimensionality of processing resources has important implications. If workload is defined as the demands of tasks imposed upon the operators' limited capacities, then adequate workload measurement must delineate and account for the various dimensions of those capacities. Evidence abounds for a multiple resource concept. The structure of resources is defined by three dimensions: processing stages (perceptual and central processing versus response selection and execution); processing modalities (visual inputs and manual responses versus auditory inputs and vocal response); and processing codes (verbal versus spatial).

The series of experiments described in the paper attempt to validate the dimensionality of this model, as part of a broader task to demonstrate its utility in workload measurement.

Results indicate that considerable data must be gathered to evaluate the utility of the model in accounting for task interference effects and workload variance.

74. Wiener, E.L., and Curry, R., Flight Deck Automation: Promises and Problems. National Aeronautics and Space Administration, Ames Research Center, NASA-TM-81206, 1980.

The paper discusses the current human factors concerns in flight-deck automation and offers some broad design guidelines. In addition, some automation-related aircraft accidents and incidents are discussed as examples of automated flight problems.

The authors voice their concerns about whether many flight-deck functions that can be automated, should be. It is questionable whether total system safety is always enhanced by allocating functions to devices rather than human operators, and perhaps flight deck automation may have already passed the point of optimality.

75. Wierwille, W., Williges, C., Survey and Analysis of Operator Workload Assessment Techniques. Patuxent River, Maryland, Naval Air Test Center, Systems Engineering Division, Technical Report No. S-78-101, 1978.

This source begins with a description of the in-depth search techniques used to compile an exhaustive bibliography and review of literature relevant to operator workload, specifically aircrew workload. The report includes four major categories of workload assessment:

1. Subjective opinion

2. Spare mental capacity

3. Primary task assessment

4. Physiological measures.

These four categories are divided into 28 specific techniques, shown in table 3. Each of these techniques is described in detail, along with an equipment description necessary for implementation, pros and cons of the technique, and suggestions for future research.

The report also acts as a guide in selecting a workload assessment methodology for aircrew flight test and evaluation by providing specific examples of research problems and determining, through the use of rating scales and checklists, the most applicable workload assessment techniques.

The authors conclude that surprisingly little data are available on the development of techniques designed specifically for flight test and evaluation. Although this survey points to several approaches that are potentially useful, no single technique can be recommended as the definitive measure of operator workload. The authors suggest the use of multiple measures selected from the four major categories described in the report.

Over 400 references relating to operator mental workload were selected and reviewed for this report.

TABLE 3. WORKLOAD METHODOLOGIES CLASSIFICATION

Major Categories

I Subjective Opinion	II Spare Mental Capacity	III Primary Task	IV Physiological Measures
	Techniques Within Categories		
Rating Scales	**Task Analytic**	**Single Measures**	**Single Measures**
Interviews	Task Component	**Multiple Measures**	FFF
Questionnaires	Time Summation Information - Theoretic	**Math Modeling**	GSR
	Secondary Task		EKG
	Nonadaptive, Arithemetic/ Logic		EMG
	Nonadaptive, Tracking		EEG
	Time Estimation		Eye and Eyelid Movement
	Adaptive, Arithmetic/ Logic		Pupillary Dilation
	Adaptive, Tracking		Muscle Tension
			Heart Rate
			Blood Pressure
			Heart Rate Variability
			Breathing Analysis
			Body Fluid Analysis
			Handwriting Analysis
			Combined Measures
			Speech Pattern Analysis

76. Wierwille, W., Physiological Measures of Aircrew Mental Workload. Human Factors, 1979, 21, 575-593.

Physiological measures of workload allow a global definition of workload in which mental workload is assumed to occur when any conglomerate of behaviors is exhibited versus the assumption that the human operator is a single-channel sampling device. In this paper, the class of workload techniques termed "physiological" can generally be discriminated from other workload techniques by the fact that the changes occurring in measures are largely involuntary.

Two major categories were formed, single measures and multiple measures, with the first of these further subdivided into 13 individual measures. Each measure is analyzed individually, even though data on more than one measure have been taken into account in a given experiment. The objective of the studies described was to find a single physiological measure that reliably reflects change in operator mental workload.

The results indicate that few, if any, of the physiological measures developed for assessment of workload are, at present, proven to the extent that they can be widely applied to aircrew mental workload problems. Those, however, that appear most promising are pupil dilation, evoked cortical potentials, and body fluid analysis. In any case, the author recommends that physiological measures should be combined with behavioral measures to obtain an adequate description of workload in an aircrew task.

77. Williges, R., and Wierwille, W., Behavioral Measures of Aircrew Mental Workload. Human Factors, 1979, 21, 549-574.

The purpose of this article is to provide an integrated review of behavioral workload measures and suggest various unresolved research issues which need to be addressed before implementation in the operational flight test and evaluation environment. Specifically, 14 methods that emphasize behavioral measures are discussed.

Of the 14 general approaches reviewed, no single technique can be recommended as the definitive behavioral measure of operator workload. Because of the multi-dimensionality of workload, it appears unlikely that any single measure will ever suffice completely. The strongest research support exists for using subjective opinions and task analytic methods involving task component/time summation.

Probably the most reliable approach is through the use of multiple measures including dimensions of subjective opinions, spare mental capacity, and primary tasks, as well as physiological correlates.

78. Young, L.R. and Sheena, D., Survey of Eye Movement Recording Methods. Behavior Research Methods and Instrumentation, 1975, Volume 7(5) 397-429.

This paper describes the current techniques for measuring eye movements, including the advantages and disadvantages of each. The physical characteristics of the eye that are used in eye movement measurement are covered. In addition, major eye movement measurement techniques are discussed with special attention given to new techniques. Trade-offs and general considerations in instrumentation selection in research conclude the paper.

Excellent illustrations and a summary table comparing most of the known eye-movement measurement techniques characterize the paper.

SUBJECT INDEX

AUTHOR INDEX

APPENDIX A

DELINEATION OF FATIGUE AND WORKLOAD INDICATORS

TABLE A-1. DELINEATION OF FATIGUE INDICATORS (Sheet 1 of 4)

Topic	Reference
TASK PERFORMANCE	
Production Rate or Productivity	Chambers, E.G. Industrial Fatigue. Occupational Psychology, Volume 35., 1961, 44-57.
Irregularities in timing of actions	Welford, A.T. Fundamentals of Skill, Methuen and Co., London, 1968.
Disorganization of skill or proficiency	Bartlett, F.C. Fatigue Following Highly Skilled Work Proc. Roy. Soc. Ser. B. Volume 131, 1943, 247-257.
Reduction of speed of task performance	Singleton, W.T. Prologue to Section 1: Man. Measurement of Man at Work, W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 15-16.
Decrease in precision or accuracy of performance	Mohler, S.R. Fatigue in Aviation Activities. Aerosp. Med. Volume 37, 1966, 722-732.
Accuracy or quality of secondary task performance	Brown, I.D. Measuring the Spare Mental Capacity of Car Drivers by a Subsidiary Auditory Task. Ergonomics, Volume 5, 1962, 247-250.

TABLE A-1. DELINEATION OF FATIGUE INDICATORS (Sheet 2 of 4)

Topic	Reference
AFFECTIVE	
Self-ratings of fatigue feelings	Kashiwagi, S. Psychological Rating of Human Fatigue. Methodology in Human Fatigue Assessment H. Hashimoto, K. Kogi, and E. Grandjean, eds. Taylor and Fransis, London, 1971, 17-21.
Complaints of Irritability depression, vague psychosomatic disorders, etc.	Schreuder, O.B. Medical Aspects of Aircraft Pilot Fatigue with Special Reference to the Commercial Jet Pilot. Aerosp. Med., Special Report Pub. 37, (4), 1966, 1-44.
Feelings of Impotence	Luongo, E.P. Work and Physiology in Health and Disease. J. Am. Med. Assoc., Volume 188, 1964, 27-32.
Complaints of Eye strain or discomfort	Bartley, S.H. The Basis of Visual Fatigue. Am. J. Optometry Arch. Am. Acad. Optometry, Monograph 30, 1947, 1-12.
Direct estimation of fatigue state	Jenny, L.L., Older, H.J. and Cameron, B.J. Measurement of Operator Workload in an Information Processing Task. NASA CR-2150, 1972.

TABLE A-1. DELINEATION OF FATIGUE INDICATORS (Sheet 3 of 4)

Topic	Reference
BEHAVIORAL	
Sensory or perceptual changes	Welford, A.T. Fundamental of Skill, Methuen and Co., London, 1968.
Slowing of psychomotor performance	
Blink value or ratio	Fukui, T., and Morioka, T. The Blink Method as an Assessment of Fatigue Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, 23-30.
Critical fusion frequency	Kogi, K. and Saito, Y. A Factor Analytic Study of Phase Discrimination in Mental Fatigue. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds. Taylor and Francis, London, 1971, 119-127.
Disintegration of complex action patterns	Hamar, H. and Novak, E. A Telemetric Method for Assessing Mental Performance. Methodology in Human Fatigue Assessment, K.Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, 129-135.
Handwriting pressure, tapping pressure and speed of finger movement	Komoike, Y. and Horiguchi, S. Fatigue Assessment on Key Punch Operators, Typists and Others. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, 101-109.
Tapping rates	Grandjean, E. Introductory Remarks.Methodology in Human Fatigue Assessment.K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, xvii-xxx.
Eye Movements	Ohtani, A. An Analysis of Eye Movements During a Visual Task. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds. Taylor and Francis, London, 1971, 167-174.
Finger Tremor	Nicholson, A.N., Hill, L.E., Borland, R.G., and Ferres, H.M. Activity of the Nervous System During the Let-down, Approach, and Landing: A Study of Short Duration High Workload. Aerospace Med., volume 41, 1970, 436-446.
Sustained concentration of attention	Takakuwa, E. Maintaining Concentration as a Measure of Mental Stress. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds. Taylor and Francis, London, 1971, 145-158.
Blocking	Bills, A.G. Blocking: A New Principle of Mental Fatigue. Am J. Psychol., volume 43, 1931, 230-245.
Withdrawl, decreased sexuality, insomnia, etc.	Mohler, S.R. Fatigue in Aviation Activities. Aerosp. Med. volume 37, 1966, 722-732.
Personality traits of extroversion	Eysenck, H.J. The Biological Basis of Personality. Charles C. Thomas. Springfield, Ill. 1967.

TABLE A-1. DELINEATION OF FATIGUE INDICATORS (Sheet 4 of 4)

Topic	Reference
PSYCHOPHYSIOLOGICAL	
Excretion of urinary metabolites	Dukes-Dobos, F.N. Fatigue from the Point of View of Urinary Metabolites. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 31-41.
Circulatory strain	Donoso, H., Apud, E., and Lungren, N.P. Direct Estimation of Circulatory Fatigue Using a Bicycle Ergometer. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds. Taylor and Francis, London, 1971, 53-60.
Lactic acid levels in the blood	Maitra, S.R., and Koyal, S.N. Experimental Studies of Muscular Fatigue of Bengalees with Increasing Work-loads under Different Environmental Conditions. Methodology in Human Fatigue Assessment, K. Hashimoto, K, Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, 71-84.
Rectal temperature	Welch, R.B., Longley, E.O., and Lomaev, O. The Measurement of Fatigue in Hot Working Conditions Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, 85-90.
Muscular tension or contraction	Heminway, A. The Physiological Background of Fatigue. Symposium on Fatigue, W.G. Floyd and A.T. Welfork, eds., H.K. Lewis and Co., London, 1953, 69-75.
Percentage of alpha rhythms in EEG	Kennedy, J.L. Some Practical Problems of the Alertness Indicator. Fatigue, W.F. Floyd and A.T. Welford, eds., H.K. Lewis and Co., London, 1953, 149-153.
Ocular muscle strain	Weston, H.C. Visual Fatigue with Special Reference to Lighting. Symposium on Fatigue, W.F. Floyd and A.T. Welford, eds., H.K. Lewis and Co., London, 1953, 117-135.
Blood condition and neuromuscular excitability	Juin, G. Protocol and Results of Medical Inquiry on the Fatigue of Aircrews Flying on Board the Boeing 707. Pilots de Ligne, Paris, December, 1961.
Disturbances of visual function	Murphy, M.R., and Randle, R.J. Effects of Fatigue on Visual Accommodation in Air Crew Members. Paper presented at the 42nd annual Meeting of the Aerospace Medical Association, Houston, Texas, 1971.

TABLE A-2. DELINEATION OF WORKLOAD INDICATORS (Sheet 1 of 6)

Topic	Reference
TASK PERFORMANCE	
Record of actual crew activities by flight segment	Anon: Some Workload and Environmental Characteristics of An Air Carrier Short Haul Turbo-Jet Operation. Summary Report on a UAL-ALPA Joint Project to Evaluate Pilot Workload on B-737 Flight Operations, United Airline, March 1969.
Accuracy of quality primary task performance	Roscoe, S.N. Assessment of Pilotage Error in Airborne Area Navigation Procedures. Tech. Rep. ARL-72-24/AFOSR-72-13, Univ. of Illinois Institute of Aviation, Savoy, Illinois, October 1972.
Speed and task completion time	Wisner, A. Electrophysiological Measures for Tasks of Low Energy Expenditure. Measurement of Man at Work, W.T. Singleton, J.G. Fox and D. Whitfield, eds., Taylor and Francis, London, 1971, 61-74.
Average duration of task elements	Leplat, J., and Pailhous, J. The Analysis and Evaluation of Mental Work. Measurement of Man at Work. W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 51-56.
Accuracy or quality of secondary task performance	Rolfe, J.M. The Secondary Task as a Measure of Mental Load. Measurement of Man at Work. W.T. Singleton, J.G. Fox and D. Whitfield, eds., Taylor and Francis, London, 1971, 135-148.
Probability of target acquisition	Zaitzeff, L.P. Aircrew Task Loading in the Boeing Multimission Simulator. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance, Brooks AFB, Texas, 1969, 8-8-3.
Threshold for detectable error	Buckner, D.N., and McGrath, J.J. A Comparison of Performance on Single and Dual Sensory Mode Vigilance Tasks. Tech. Rep. 8, Human Factors Research, Inc., Los Angeles, 1961.
Completeness and accuracy	Jenney, L.L., Older, H.J., and Cameron, B.J. Measurement of Operator Workload in an Information Processing Task. NASA CR-2150, 1972.

TABLE A-2. DELINEATION OF WORKLOAD INDICATORS (Sheet 2 of 6)

Topic	Reference
BEHAVIORAL	
Finger tremor	Nicholson, A.N., Hill, L.E., Borland, R.G., and Ferres, H.H. Activity of the Nervous System During the Let-down, Approach and Landing: A Study of Short Duration High Workload. Aerosp. Med., volume 41, 1970, 436-446.
Critical fusion frequency	Rey, P. The Interpretation of Changes in Critical Fusion Frequency. Measurement of Man at Work, W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 115-120.
Eye movements and fixations	Shackel, B. Electro-oculography: The Electrical Recording of Eye Position. Proceedings of the Third International Conference on Medical Electronics, 1966, 322-335.
Intonations of speech	Luk'yanov, A.N., and Frolov, M.V. Signals of Human Operator State. NASA TT F-609, 1969.
Pilot evaluation of handling qualities	Cooper, G.E., and Harper, R.P., Jr. The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.
Pilot evaluation of task difficulty	Krzanowski, W.J., and Nicholson, A.N. Analysis of Pilot Assessment of Workload. Aerosp. Med., volume 43, 1972, 993-997.
Cognitive, perceptual, sychomotor, and sensory task performance	Jenney, L.L., Older, H.J., and Cameron, B.J. Measurement of Operator Workload in an Information Processing Task. NASA-CR-2150, 1972.

TABLE A-2. DELINEATION OF WORKLOAD INDICATORS (Sheet 3 of 6)

Topic	Reference
AFFECTIVE	
Self-ratings of perceived exertion	Borg, G. Psychological and Phsyiological Studies of Physical Work. Measurement of Man at Work. W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 121-128.
Operator preferred levels of work intensity	
Direct estimates of task difficulty	Jenney, L.L., Older, H.J., and Cameron, B.J. Measurement of Operator Workload in an Information Processing Task. NASA-CR-2150, 1972.

TABLE A-2. DELINEATION OF WORKLOAD INDICATORS (Sheet 4 of 6)

Topic	Reference
TASK REQUIREMENTS INPUT	
Task requirements by flight segment	Zipoy, D.R., Preselaar, S.J., Gargett, R.E., Belyea, I.L., and Hall, S.J. Integrated Information Presentation and Control System Study. AFFDL-TR-70-79, volume I, Air Force Flight Dynamics Lab, 1970.
Task completion time versus time available	Price, H.E., Honsberger, W.D., and Ereneta, W.J. A Study of Potential Roles of Supersonic Transport Crews and Some Implications for the Flight Deck. NASA-CR-561, 1966.
Task-time stress index	Klein, T.J. A Workload Simulation Model for Predicting Human Performance Requirements in the Pilot-Aircraft Environment. Paper presented to the Human Factors Society's 14th Annual Convention San Francisco, October 13 to 16, 1970.
Crew task demand elements	Gartner, W.B., Ereneta, W.J., and Donohue, V.R. A Full Mission Simulation Scenario in Support of SST Crew Factors Research. NASA CR-73096, 1967.
Number of input channels and signal rate	Hartman, B.O. Time and Load Factors in Astronaut Proficiency, Symposium on Psychophysiological Aspects of Space Flight, B.E. Flaherty, ed., Columbia Univ. Press, New York, 1961, 278-308.
Amount of task information available and index of quality	Leplat, J., and Pailhous, J. The Analysis and Evaluation of Mental Work. Measurement of Man at Work. W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 51-56.

TABLE A-2. DELINEATION OF WORKLOAD INDICATORS (Sheet 5 of 6)

Topic	Reference
PSYCHOPHYSIOLOGICAL	
Heart rate	Corkindale, K.G., Cumming, F.G., and Hammerton-Fraser, A.M. Physiological Assessment of Pilot Stress During Landing. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance. Brooks AFB, Texas, 1969, 9-9-4.
Electrical activity of the brain	Haider, M. Comparison of Objective and Subjective Methods of the Measurement of Mental Workload. Displays and Controls, R.K. Bernotat and K.P. Garnter, eds., Swets and Zeitlinger, Amsterdam, 1972, 17-27.
Muscle activity or tension EMG	Corkindale, J.G., Cumming, F.G., and Hammerton-Fraser, A.M. Physiological Assessment of Pilot Stress During Landing. In Proceedings of the 56th AGARD Conference on Measurement of Aircrew Performance. Brooks AFB, Texas, 1969, 9-9-4.
Skin resistance, GSR	Murrell, K.F. Temporal Factors in Light Work. Measurement of Man at Work, W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 45-50.
Blood pressure	Ettema, J.H., Zielhuis, R.L. Physiological Parameters of Mental Load. Methodology in Human Fatigue Assessment, K. Hashimoto, K. Kogi, and E. Grandjean, eds., Taylor and Francis, London, 1971, 137-144.
Sinusarrythmia	Kalsbeek, J.W. Sinusarrythmia and the Dual Task Method in Measuring Mental Load. Measurement of Man at Work, W.T. Singleton, J.G. Fox and D. Whitfield, eds., Taylor and Francis, London, 1971, 101-114.
Evoked cortical potential	Wisner, A. Electrophysiological Measures for Tasks of Low Energy Expenditure. Measurement of Man at Work, W.T. Singleton, J.C. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 61-74.
Urinary excretion of catecholamines, metabolites, electrolytes, and simple compounds	Hale, H.B., Williams, E.W., Smith, B.N. and Melton, C.E. Excretion Patterns of Air Traffic Controllers. Aerosp. Med., volume 42, 1971, 127-138.

TABLE A-2. DELINEATION OF WORKLOAD INDICATORS (Sheet 6 of 6)

Topic	Reference
PSYCHOPHYSIOLOGICAL (Continued)	
Parotid fluid excretions	Warren, B.H., Ware, R.W., Shannon, I.L., and Leverett, S.D. Determination of Inflight Biochemical Responses Utilizing the Parotid Fluid Collection Technique. Aerosp. Med., volume 37, 1966, 796-799.
Pupil size	Kahneman, D., Tursky, B., Shapiro, D., and Crider, A. Pupillary, Heart Rate, and Skin Resistance Changes During a Mental Task. Exptl. Psychol., volume 79, 164-167.
Relative metabolic rate oxygen uptake	Bonjer, F.H. The Contribution of Work Physiology to the Evaluation of Man-Machine Systems. Measurement of Man at Work, W.T. Singleton, J.G. Fox, and D. Whitfield, eds., Taylor and Francis, London, 1971, 93-100.
Ventilatory rate	Sharkey, B.J., McDonald, J.F., and Corbridge, L.G. Pulse Rate and Pulmonary Ventilation as Predictors of Human Energy Cost. Ergonomics, volume 9, 1966, 223-227.
Level of activation	Duffy, E. Activation and Behavior. John Wiley and Sons, New York, 1962.
Combination of above patterns	Cumming, F.G., and Corkindale, J.G. Physiological and Psychological Measurements of Pilot Work-. load Tech. Memorandum HFG 101, Royal Aircraft Establishment, November 1967. Benson, A.J., Huddleston, J.H., and Rolfe, J.M. Psycho-physiological Study of Compensatory Tracking on a Digital Display. Human Factors, volume 7, 1965, 457-472. Spyker, D.A., Stackhouse, S.P., Khalafalla, A.S., and McLane, R.C. Development of Techniques for Measuring Pilot Workload. NASA CR-1888, 1971.